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THE EVALUATION OF ADVANCED INDUSTRIAL MATERIALS FOR USE IN NAVIGATION BUOY DESIGN

January 1991

Prepared for: Transportation Development Centre
Policy and Coordination Group
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by
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The contents of this report reflect the views of the Advanced Materials Engineering Centre and not necessarily the official view or opinions of the Transportation Development Centre of Transport Canada.

Un sommaire en français est inclus avant la table des matières.

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16. Abstract

The objective of this project was to evaluate the use of advanced industrial materials for use in the Canadian Buoyage System. In preparation of the conceptual buoy designs presented in the report, an extensive literature search as well as site visits to various Coast Guard bases were conducted. The investigation determined that corrosion was the major limiting factor in the maintenance of the current buoys. The Advanced Industrial Materials Technologies Review demonstrated that several manufacturing processes show promise in enhancing the performance of the buoyage system. The processes are rotational molding, filament winding, hand lay-up/spray-up and extrusion. All of these will allow fabrication of non-corrosive buoys. Buoys constructed of advanced industrial materials would be non-corrosive and represent approximately a 50% weight reduction as well as a significant reduction in maintenance costs.

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16. Résumé

La présente étude avait pour objet d'examiner les possibilités d'utiliser des matériaux industriels de pointe dans le système de balisage canadien. Avant d'entreprendre les études des modèles de bouées présentés dans ce rapport, les chercheurs ont fait une recherche documentaire poussée et ont poursuivi leur investigation dans plusieurs bases de la GCC. Ces recherches ont permis d'établir que la corrosion est la principale cause d'avarie des bouées. Les recherches sur les matériaux et technologies de pointe ont révélé qu'il serait possible, grâce à divers procédés de fabrication, d'améliorer la tenue en service des bouées. En effet, les procédés de rotomoulage, d'enroulement filamentaire, de moulage au contact ou par projection et d'extrusion permettent tous de fabriquer des bouées en matériaux de pointe qui ont non seulement l'avantage d'être insensibles à la corrosion, mais sont à peu près de moitié moins lourds que les matériaux actuellement en usage. L'utilisation de tels matériaux réduirait considérablement les coûts d'entretien des bouées.

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SUMMARY

The Advanced Materials Engineering Centre (AMEC) was awarded the task of performing a systematic review of advanced materials and the associated technologies that would be applicable to the Canadian Buoyage System for the Canadian Coast Guard Aids and Waterways Group.

To achieve this objective, first AMEC had to identify the limitations and weaknesses of the present buoy materials. Second, AMEC had to identify suitable advanced industrial materials technologies and process alternatives. If any technologies were found to be viable, AMEC was to provide a portfolio of conceptual designs.

To identify weaknesses and limitations in the present buoyage system, AMEC conducted an extensive literature search in conjunction with site visits to five Canadian Coast Guard (CCG) Bases. The initial assumption was that corrosion was the major weakness of the present buoyage system and it was responsible for most of the limitation imposed on the present buoys. The literature search revealed that maintenance of the buoys was a major limitation and the driving factor was corrosion. The search revealed that what work had been done to date with plastic buoys had been mainly with non-fibre reinforced plastics. Trinity House in England had worked with fibre reinforced buoys but restricted its processing techniques to that of hand lay-up with rovings and chopped strand mat.

Both the Canadian and the U.S. Coast Guard have experimented with non-fibre reinforced plastic buoys. The negative comments concerning these buoys were mainly related to design problems, not material problems. To confirm the findings of the literature search, five CCG Bases were visited to verify what problems the CCG was experiencing with its present buoys. The Navigational Aids Test Establishment (NATE) in Cardinal, Ontario, was visited to see what implication solar panels might have on any new buoyage system. Dartmouth, St. John's, Quebec City and Charlottetown CCG Bases were also visited to identify problems related to the current buoyage system. The site visits reconfirmed that corrosion was the driving factor for maintenance, however, in Quebec, ice damage was found to be an equally contributing factor to the maintenance problem and it appeared that future use of solar panels would have no adverse effect on the buoyage system.

The information gathered from the literature search and site visits allowed an informed review of existing advanced industrial materials technologies and processes for possible use in the Canadian Buoyage System. The use of an advanced industrial material would eliminate the major corrosion problem. This fact has been known for quite a while as evidenced by the past attempts at using alternative materials. It appears though that these previous buoys were only designed to eliminate the corrosion problems, without concern for the overall physical environment of the buoys. The literature search revealed several advanced industrial materials and processes: injection molding, compression molding, transfer molding, resin injection molding, resin transfer molding, blow molding, rotational molding, thermoforming, filament winding, hand lay-up/spray-up, pultrusion and extrusion.

Several advanced industrial materials were identified as viable these being glass fibres in a thermoset or thermal plastic resin matrix.

Each process had its own inherent limitation with respect to its ability to fabricate a buoy. Various processes had limitations on size of components, productivity, resin type, fibre type, etc.

Only four processes are potentially viable: rotational molding, filament winding, hand lay-up/spray-up and extrusion.

Charlottetown CCG Base in P.E.I. presently has a dozen or so extruded plastic lighted ice spar buoys which to date are essentially maintenance free. However, due to the high initial cost of these buoys, the CCG finds it prohibitive to purchase more.

To verify the suitability of glass fibre thermoset resin buoys, a preliminary design analysis was conducted by AMEC on two conceptual buoy designs – a 1.0 m. ice spar and a 2.9 m. light and sound buoy. Design loadings determined from the CCG "Navigational Buoy Design Manual" and finite element analysis were used to determine the suitability of the two buoys manufactured with continuous glass fibre reinforcing in an epoxy resin matrix.

Preliminary design calculations indicated that an E-Glass epoxy laminate ice spar would have a wall thickness of approximately 12 mm and weigh 1622 kg. The light/sound buoy would have a wall thickness of 8 mm and weigh 1705 kg, which is about a 60% weight reduction. This large weight reduction would result in easier handling of the buoys and prolonged mooring life. Due to the inherent non-corrosiveness of fibre reinforced plastics, maintenance requirements would only be that of de-fouling marine growth and battery and lantern repairs where applicable. This should result in a maintenance cost reduction of approximately 600%. The investigation into the use of alternative materials for "short range floating aids to navigation" has shown that, as in the aerospace industry, advanced industrial materials do have a place in future buoy design and that with the proper design and manufacturing process, they can offer substantial cost savings in the maintenance of short range floating aids by the Canadian Coast Guard.

SOMMAIRE

L'AMEC (Advanced Materials Engineering Centre) a mené pour le compte de la Direction des aides et voies navigables de la Garde côtière canadienne une étude systématique des matériaux et technologies de pointe en vue de déterminer lesquels seraient susceptibles d'améliorer le système de balisage canadien.

A cette fin, les chercheurs devaient d'abord définir les limites et les faiblesses des matériaux actuellement en usage dans la fabrication des bouées. Ils devaient ensuite déterminer si, dans la gamme de nouveaux matériaux industriels et de procédés de mise en forme, certains conviendraient à cet usage. Le cas échéant, ils devaient enfin proposer divers modèles de fabrication.

Pour définir les limites et les faiblesses de l'actuel système de balisage, les chercheurs ont parcouru une vaste documentation et se sont rendus sur les lieux de cinq bases de la GCC. L'hypothèse de départ était que la principale faiblesse des bouées existantes est leur sensibilité à la corrosion, et que celle-ci constitue la principale limite du système de balisage. Les recherches documentaires ont confirmé que la nécessité d'entretien des bouées constituait une entrave majeure à l'efficacité du système de balisage, et qu'elle avait comme principale cause la corrosion. On a trouvé qu'à ce jour, la recherche expérimentale dans ce domaine avait surtout porté sur la fabrication de bouées en plastique non renforcé par des fibres. La société anglaise Trinity House a mis au point des bouées en matériau renforcé par des fibres, mais le seul procédé de fabrication qu'elle a expérimenté est le moulage à la main par imprégnation d'une armature de roving ou de fibres coupées réunies en nappe.

La Garde côtière canadienne et la Garde côtière américaine ont toutes deux utilisé à titre expérimental des bouées en matière plastique non renforcée par des fibres. Les problèmes posés par ces bouées étaient plutôt liés à leur conception qu'au matériau constitutif. Pour vérifier la validité des résultats de la recherche documentaire, les chercheurs se sont rendus dans cinq bases de la GCC, en vue d'y constater les problèmes que posent les bouées utilisées actuellement. Ils se sont rendus au Centre d'essais des aides à la navigation de Cardinal en Ontario, afin de vérifier les effets éventuels de panneaux solaires sur tout nouveau système de balisage. Ils ont vérifié quels problèmes présente le système de balisage actuel dans les bases de Dartmouth, St. John's, Québec et Charlottetown. Ces investigations ont confirmé que la corrosion est le principal facteur de détérioration, sauf à Québec où les glaces causent des dommages tout aussi importants que la corrosion. Il semble que l'utilisation de panneaux solaires n'aurait aucun effet négatif sur le système de balisage.

Les données recueillies au cours de la recherche documentaire et lors des visites des bases de la GCC ont permis d'examiner en connaissance de cause les matériaux et procédés industriels de pointe envisagés pour le système de balisage canadien. On sait depuis longtemps, comme en témoignent diverses expériences, que l'utilisation de ces nouveaux matériaux permettrait d'éliminer le problème principal, qui est celui de la corrosion. Il semble toutefois que dans les diverses tentatives en ce sens, on ait eu recours à ces matériaux dans le seul but d'enrayer le problème de corrosion, sans tenir compte des autres facteurs de détérioration. Les recherches ont révélé l'existence d'une diversité de matériaux et de procédés de fabrication industriels de pointe: moulage par compression, moulage par transfert, moulage par injection, moulage par soufflage, rotomoulage, thermoformage, enroulement filamentaire, moulage au contact ou par projection, pultrusion et extrusion.

Plusieurs des nouveaux matériaux industriels conviendraient pour la fabrication de bouées; il s'agit de résines thermoplastiques ou thermodurcissables renforcées par des fibres de verre.

Quant aux procédés de fabrication, chacun comporte ses limites intrinsèques, que ce soit par rapport à la dimension des objets qu'il permet de fabriquer, à la productivité, au type de résine ou de fibre qui peuvent être utilisées, etc. Quatre procédés seulement conviendraient à l'usage considéré: le rotomoulage, l'enroulement filamentaire, le moulage au contact ou par projection et l'extrusion.

Les installations de la base de Charlottetown comptent environ une douzaine de bouées lumineuses à espar en plastique extrudé, qui n'ont jusqu'à maintenant exigé pratiquement aucun entretien. Toutefois, la GCC n'a pas l'intention d'acquérir d'autres bouées de ce genre, en raison du coût d'achat qu'elle juge prohibitif.

Pour vérifier l'aptitude à l'emploi d'une résine thermodurcissable à armature de fibres de verre, l'AMEC a fait les études préliminaires de deux modèles de bouées: une bouée à espar de 1 m et une bouée lumineuse à signal sonore de 2,9 m. Les charges nominales tirées du manuel de la GCC intitulé: ‹‹Critères des conceptions et exigences opérationnelles pour bouées de navigation›› et une analyse par la méthode des éléments finis ont servi à déterminer l'aptitude à l'emploi des deux bouées fabriquées de résine époxydique à armature de fibres de verre continues.

D'après les calculs des études préliminaires, une bouée à espar en verre E-résine époxydique aurait une paroi d'environ 12 mm d'épaisseur et atteindrait un poids de 1622 kg. Une bouée lumineuse à signal sonore aurait une paroi de 8 mm d'épaisseur et atteindrait un poids de 1705 kg, ce qui représente un allègement d'environ 60 p. 100 par rapport aux bouées actuellement en usage. Une telle réduction de poids faciliterait la manutention et augmenterait la durée de vie utile de la bouée. Comme le plastique à armature de fibres de verre est un matériau non sensible à la corrosion, l'entretien serait limité à l'enlèvement des organismes aquatiques adhérents et éventuellement au remplacement de l'accumulateur et de la lanterne, ce qui devrait entraîner une réduction des coûts d'entretien d'environ 600 p. 100.

Cette étude a révélé que l'utilisation de matériaux industriels de pointe peut être avantageuse dans la fabrication d'aides flottantes à la navigation de faible portée comme dans l'industrie aérospatiale, dans la mesure où elle s'accompagne d'une bonne conception et d'un choix judicieux des procédés de fabrication, et qu'elle permettrait par surcroît de réaliser des économies importantes en matière d'entretien pour la Garde côtière canadienne.

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1. INTRODUCTION

The objective of this report is to present a comprehensive review of advanced industrial materials and their associated technologies as they apply to the Canadian Buoyage System. It has been prepared to assist Canadian Coast Guard Aids and Waterways Group in its effort to develop regulations for safe and efficient conduct of marine activities in waters under Canadian jurisdiction.

The report covers all the major methods of fabrication technologies for composite materials of fibre reinforced plastics as they relate to buoy design. An extensive literature search was conducted to find relevant technologies that could be applied to the manufacture of buoys with advanced materials. To better understand the problems that the CCG was encountering with its present buoyage system, site visits to various Coast Guard Bases were conducted. To address these problems, we have developed a portfolio of conceptual designs and a technology assessment of the use of advanced materials in navigational buoy design.

2. LITERATURE SEARCH

The purpose of the literature search was to determine: the existing problems with navigational buoys, the buoys' performance requirements, previous experience with plastic buoys, and information relating to the use of plastics in marine applications.

The literature search first examined the problems that are experienced with existing buoys. It was found that buoys required annual maintenance, and the driving force for the maintenance was corrosion. It was also found that the service interval was influenced by mooring wear, battery and light replacement, and maintenance of sound apparatus (bells and whistles).

Trinity House, the navigational authority in the U.K., has had some experience with plastic buoys. In one case a glass reinforced polyester was used, and fabricated in the traditional boat building fashion. The buoy body was reinforced with woven roving and chopped strand mat and a gel-coat was applied. The body was filled with foam so that in the event of an accident it would not sink. It was their experience that the buoy required as much maintenance as a conventional buoy due to the repair needed to the gel coat. As the gel coat was chipped or cracked it needed to be replaced. Another observation was that the buoy was more lively in light seas due to its reduced weight, making it more difficult to recover for servicing. This is primarily a design issue and the performance could be improved by a modification of the hull configuration.

The Canadian Coast Guard has also had some experience with plastic buoys. Two studies were found, both involving the use of cross-linked polyethylene. One study evaluated a spar buoy which would be used to replace the Ottawa River Spar, the other study evaluated a hemispherical swift current buoy. The findings for the spar buoy were positive. The buoy was found to be lighter and easier to handle than its steel counter part. There was no damage or deterioration of any of the test specimens used. The only negative comments were a result of design detail factors, such as the location of lifting eyes. The cost of the plastic spar buoy was $297 as compared $98 for the steel buoy. It was stated that the cost could be reduced by as much as 25%, if the buoys were purchased in quantity. The findings for the hemispherical swift current buoy were less positive. This buoy was procured from the United States Coast Guard at a cost of $384. It was designed with a thin plastic shell (5 mm) around a steel frame. The main criticisms were that the buoy was easily damaged, primarily as a result of the thin hull. It was suggested that a thicker hull be used as the main structural component and that the steel frame be eliminated, it was felt that such a configuration would be lighter and more robust. Other criticisms with the buoy were due to its instability in currents greater than 2.5 m/s. This is primarily a design issue and the performance could be improved by a modification of the hull configuration.

The literature search then focused on the material and manufacturing techniques available for the fabrication of buoys. The materials included thermoplastic and thermoset resins, and additives for colour and ultra-violet protection. Of the thermoplastics, polyethylene appeared to be the most commonly used in marine environments. For the thermoset resins, polyester and epoxy were the most commonly used. Polyester resins were found to be less stable in a high moisture environment. However,the advantage of polyester is that it is much cheaper than epoxy. For the manufacturing of buoys all major plastic manufacturing techniques were looked at. Some information was found for the manufacture of canoes and boats. Boats and canoes are relatively shallow structures which are open, where as buoys are closed hull and tend to be deeper, hence the manufacturing processes used for boats may not be applicable to

buoys. As an example, thermoforming, which is used quite often for the manufacture of canoes, is not well suited for making buoys.

3. SITE VISITS

The first step to take in addressing the viability of using composite materials in the navigational buoy system is to identify what problems there are with the existing buoys (if any) and identify what problems may be addressed through the use of alternative materials.

The initial assumption was that the current use of steel required a significant amount of maintenance and when reviewing the general cost of maintaining the buoyage system, we saw that of the $141 million, noted in the Auditor General's report for aids and waterways, over 50% or $83.1 million would be spent on operating cost for the vessels. At this point the assumption was made that a large savings could be made by reducing the need for annual maintenance on the buoys and thereby reducing the vessel requirements – which represent a large cost savings opportunity.

To validate our initial assumption, it was decided to conduct site visits to various Canadian Coast Guard Bases. Five sites were chosen:

Navigational Aids Test Establishment (NATE) in Cardinal, Ontario
- To review what implications solar panels might have on any new designs

Dartmouth CCG Base, Nova Scotia
- Maintenance requirements of buoys
- Facilities available for maintenance
- General comments of current buoy design

St. John's CCG Base, Newfoundland
- Maintenance requirements of buoys
- Facilities available for maintenance
- Ice problems
  (i.e. floating pack ice)
- General comments of current buoy design

Quebec City CCG Base, Quebec
- Maintenance requirements of buoys
- Facilities available for maintenance
- Ice problems
  (i.e. ice jams)
- General comments of current buoy design

Charlottetown CCG Base, Prince Edward Island
- Maintenance requirements of buoys
- Facilities available for maintenance
- Ice problems
  (i.e. ice jams)
- Experience with plastic buoys
- General comments of current buoy design

Dartmouth Coast Guard Base appeared to have the most comprehensive maintenance facility. Dartmouth was the only base to have an adequate sandblasting site, but they are planning to move the operation indoors due to complaints by local residents.

Facilities available to St. John's CCG personnel are limited. The only time that sand blasting can be done is when no ships are tied up to the wharf and winds are favorable. This results in very few of the buoys being sand blasted before repainting. St. John's CCG Base is presently doing 2-year patch work, preventative maintenance every 3 years, and major overhauls every 5 years. They have lost 2 buoys in 7 years. On a 2 - 3 week trip, St. John's CCG will place and/or retrieve 50 - 60 buoys.

In Quebec, major problems encountered by buoys are swift currents, fast moving ice floes and build up of slush on buoy surface. A buoy with a radar reflective signature signal was felt to be good. The personnel in Quebec are very skeptical of a fiberglass buoy being able to withstand the ice conditions in the St. Lawrence River. The present steel ice spars are severely dented, but function. Alternative material must be able to sustain a large amount of deformation without failure.

CCG personnel in P.E.I. stated the present plastic buoys are essentially maintenance free. Colour fading is insignificant. Handling of the buoy for retrieval and deployment is somewhat tricky; relocation of the lifting lugs may improve this problem. The major problem with these plastic buoys is that a product designed for a different application has been converted to make a buoy. It appears a plastic pipe has been converted to produce a spar buoy. It should be noted that the majority of the buoys in P.E.I. are maintained by private contractors (e.g. fishermen). The introduction of a lighter buoy would be advantageous to these small contractors. In addition, a buoy constructed of a material that required no special equipment (e.g. sand blasting, paint booth) would be useful. CCG personnel indicated that their office would be very interested in seeing an Ottawa River Spar constructed in a plastic material.

To summarize the findings of the site visits, the following points can be stated:

1. Main driving factor for maintenance was corrosion, except in Quebec City where ice damage was equally a factor, influencing maintenance.

2. A large number of the buoys were in seasonal locations and would require seasonal deployment and retrieval.

3. Mooring was a limiting factor in frequency of maintenance requirements. By this we mean that the maximum life expectancy of a mooring, prior to maintenance, is 3 - 5 years.

4. Current buoys, in general, fared better in winter conditions than was originally assumed. This unexpected revelation came about as a result of a strike of ships' hands aboard CCG vessels, which meant the buoys were left in longer than normal in ice conditions but showed little damage.

5. Why ice spars used in winter locations were not used year round was unexplained.

6. Sandblasting as required in the general maintenance of the steel buoys is a problem.
   - Dartmouth is planning to move operation indoors
   - St. John's has very limited opportunities to sandblast due to existing site conditions.
   - Charlottetown and Quebec City sandblast sporadically on the wharf.

7. Current plastic buoys used in P.E.I. are maintenance free. However, the cost of buying new ones is prohibitive.

8. All Bases voiced an interest in obtaining an Ottawa River Spar of plastics construction.

9. A buoy of reduced weight was seen as advantageous.

10. The current high performance paint system appears quite effective in the regions using it (i.e. Saint John's and Charlottetown).

The use of an advanced material (a material lighter and stronger than aluminum) could potentially address several of the key points related to lowering maintenance costs. When looking at the material properties, one sees that from a physical property perspective a buoy of adequate strength should be obtainable with a significant weight savings. However, because composite products are highly tailorable, the final properties of a buoy can only be reviewed after the preliminary design.

- A composite buoy will not corrode.

- A composite buoy, due to its reduced weight, should reduce loading on the moorings and lengthen maintenance intervals.

Therefore, one should be able to adequately design a buoy with advanced materials, but how does one economically fabricate one and what will the design be like? To address these questions, one has to review the technologies available to manufacture a buoy of advanced materials, the costs associated with each technology and the advantages and disadvantages.

4. ENGINEERING PLASTICS

A major advantage that engineering plastics have over traditional materials, like steel, is their ability to be modified for different applications. So, there is a broader range of properties which must be considered. Therefore it becomes much more important to identify a set of criteria by which the differing plastics can be compared. These criteria include not only the properties of the material being evaluated, but also the environmental factors. Buoys are exposed to low temperatures, sun light, moisture, ice impacts, incidental impacts, and marine growth. Some of these conditions can have adverse affects on the performance of buoys. For this reason we will look at the following key factors in the application of plastics to buoys:

- Reinforcement
- Resin
- UV inhibitors
- Impact strength
- Ultimate strength
- Moisture absorption
- Marine growth
- Colour stability

4.1 Reinforcement

Reinforcement fibres within the matrix can be in the form of continuous fibres, short chop strand fibres or broad goods (i.e. cloth like). The fibres can be glass, carbon, aramid, high density polyethylene (e.g. Spectra or Dyneema) and even metallic. For the purposes of this report metallic reinforcements will not be discussed. The matrix of a composite is essentially a homogeneous resin or polymer material in which the fibre system of a composite is imbedded. In a composite material, the load is carried by the fibres and the resin matrix transfers the load from fibre to fibre throughout the composite. The dominant component contributing to the physical properties of a composite is the fibre. The primary groups of fibres to be considered in this report are: glass, carbon and aramid fibres.

Glass fibres are unique in that they exhibit the familiar bulk glass properties (transparency, stability, inertness, hardness and resistance to chemical attack) as well as fibre properties (strength, flexibility, lightness of weight and processability). Typical fibre diameters range from 3 - 20 μm. There are three classifications of glass: E-Glass, S-Glass and C-Glass. E-Glasses are used as general purpose fibres when strength and high electrical resistivity are required. In applications where high tensile strength is required S-Glass is used. C-Glass is used when chemical stability is required in a corrosive environment.

Carbon and graphite fibres offer the highest modulus and highest strength of all reinforcing fibres. The terms carbon and graphite are often used interchangeably. The basic differences lie in the temperature at which the fibres are made and heat treated and the quantity of elemental carbon produced. Carbon fibres are typically carbonized at around 1315°C and contain 93 - 95% carbon. Graphite fibres are carbonized at 1900° to 2480°C and contain 99% carbon. Aggressive development of new processes promise significant improvements in performance/cost ratio. The cost of carbon fibres have dramatically dropped in recent years while at the same time physical properties have increased. In the 1970s, carbon fibres costs exceeded $200/kg; now, carbon fibres sell for as low as $9/kg.

Aramid fibres are highly oriented organic materials derived from polyamide that incorporate an aromatic ring structure and are high strength, high modulus fibres. Two popular brand names of these fibres are Kevlar and Nomex. The aramid fibre is unusual in that technically it is a thermal plastic. However, when heated, instead of melting it decomposes before reaching its projected melting temperature. The fibres have linear tensile stress/strain behaviour to failure, however, unlike inorganic fibres, they are surprisingly damage tolerant. The compression strength of aramid fibres is far lower than inorganic fibres and they have a tendency to absorb water. Nevertheless, they are widely used for mooring scientific buoys.

Olefins such as Allied Chemical's Spectra are coming into use. These high density polyethylene based fibres have outstanding tensile and impact strengths but usually perform poorly in creep. Thus, they may be useful for impact hulls but are likely poor for mooring.

Table 4-1 outlines a few common fibres and their relative properties.

Table 4-1: Fibre Properties

Fibre	Price per Kg ($/Kg)	Modulus (GPa)	Tensile Str. (MPa)	Max. Strain (%)	Diameter (μm)	Max. Temp. (°C)	Equil. Moisture (%)	Density (g/cm³)	Manufacturer	Trade Name
Glass										
E	2.19	69	1510	4.8	4-13	590	0.0	2.58	PPG, OCF	—
S-2	14.25-16.25	87	4500	4.5	4-13	760	0.0	2.4	PPG, OCF	—
Organic										
Aramid	53-73	125	2750	2.9	12	250	4.3	1.44	DuPont	Kevlar 49
Aramid	53-73	185	3500	1.9	—	250	1.5	1.47	DuPont	Kevlar 149
Olefin	60-78	365	5800	1.6	—	—	—	1.58	Dow	PBO
Olefin	60-78	330	4200	1.3	—	—	—	1.58	DuPont	PRT
Olefin	60-78	83-100	2500-3100	2.2-2.5	—	—	—	1.4	Celanese	LCP
Olefin	60-78	170	3000	2.0	—	—	—	0.97	Allied Chem.	Spectra 1000
Inorganic										
Carbon-PAN	60-163	230-400	2800-4200	1.3-1.65	5.8	600	0.0	1.76	Toray	HS
Carbon-PAN	60-163	230-400	4300-5700	1.6-1.8	5	600	0.0	1.81	Toray	IM
Carbon-PAN	60-163	230-400	2500-3800	0.7	8	600	0.0	1.81	Toray	HM
Carbon-Pitch	120-180	827	3400	0.6	10	500	0.0	2.19	DuPont	
Alumina	550	380	1380	—	20	1000	—	3.7	DuPont	Fibre FP
Boron	1500-1650	400	3450	—	4-6	—	—	2.5	Textron	Boron
Quartz	275	69	6000	—	9	1050	—		JPS Glass Fab	Astroquartz
SiC	640-770	193	2950	—	20	1000	—	2.8	Dow Corning	Nicalon

4.2 Resins

A polymer resin is by definition a very large molecule composed of many small repeating molecular units called monomers. Natural forms of polymers are silk, rubber and wool. There are two general categories of polymer resin: thermosets and thermoplastics. Thermoplastics have a linear molecular structures and can be elevated to a temperature where they melt and can be reprocessed with no deterioration in the physical properties. A thermoset cures with the addition of heat at which point, due to cross linking of the covalent bonds, the resulting material cannot be reprocessed.

Thermosets cost less than $10/kg and are cheaper than thermoplastics, however, a growing number of thermoplastics can now be purchased for less than $10/kg. As a rule, most continuous fibre reinforced composites are made with thermoset resins, but recent developments in thermoplastic technology are making them more competitive in this area.

There are several factors that give thermoplastics an advantage over thermosets: thermoplastics are easier to repair, have easier fabrication, and have better impact resistance. A buoy made from thermoplastics can be expected to cost up to three times more for materials than one made from a thermoset resin. However, the fabrication costs would be lower and the long-term maintenance costs would be lower. So despite the higher initial cost, the thermoplastics offer long-term advantage.

Table 4-2 shows the key advantages and disadvantages of some of the common resins available. Table 4-3 shows the cost and properties of several types of resins. Table 4-4 shows the relationship between process and matrix/reinforcement.

MATERIALS	KEY ADVANTAGES	NOTABLE LIMITATIONS
THERMOPLASTICS		
Polyamides	High strength, good wear resistance	Very high cost, very difficult to process and fabricate
Polycarbonates	Very good engineering properties including creep and fatigue, dimensional stability	Moderate cost. Poor solvent resistance, subject to stress crack
High density polyethylene	Good toughness, low cost, readily molded, or extruded	Lower strength than polyamides or polycarbonates.
Polyurethane	Tough, abrasion fatigue resistant, high tear strength, solvent and ozone resistant	Polyester types are degraded by moisture. Difficult to process
THERMOSETS		
Epoxy	High strength and toughness, good dimensional stability, ease of processing	Moderate cost
Polyesters	Low cost, rigidity, some formulations are weather resistant	UV aging (depending on the formulation

Table 4-2: Resin Advantages and Disadvantages

Table 4-3: Resin Properties

Resin	Price per Kg. ($/Kg)	Modulus (GPa)	Tensile Str. (MPa)	Heat Distortion Temp. (°C)	Strain at Failure (%)	Density (g/cm^3)	Manufacturer	Trade Name
Thermosets								
Unsaturated Polyesters	1.10-1.70	3.5	89.6	68-120	1.3	—	Amoco	High Mod. Type
Unsaturated Polyesters	1.10-1.70	0.35	20.7	68-120	4.0	—	Amoco	Low Mod. Type
Vinyl Esters	2.80-3.00	3.6	80.0	104-160	4.0	—	Dow	Derakane
Phenolics	1.30-1.50	5.0	50	73-80	1.6	—	Plastics Eng.	02300
Phenolics	1.30-1.50	—	38	73-80	—	—	Fiberite	Bordon SC1008
Dicyclopentadiene	3.00	—	—	103	—	—	—	—
Polyurethanes	2.20-2.90	—	86.9	135-150	3.5	—	—	—
Epoxies	2.80-6.00	—	75.8	150-280	4.9	1.2	DGEBA	DETDA
Epoxies	2.80-6.00	—	48.3	150-280	1.5	1.2	TGMDA	DDS
Bismaleimides	30.00	—	35.9	270-285	1.4	1.25	BMI	MDA
Bismaleimides	30.00	—	86.2	270-285	2.5	1.25	BMI	DAB
Polyimides	41.00	3.8	102	260	14	1.32	Avamid	K-III
Polyimides	41.00	4.1	69	260	1.0	1.32	Skybond	701
Thermoplastics								
Polypropylene	1.10	—	—	50-65	—	—	—	—
Polyesters	1.50-3.20	8.8	130	40-85	—	1.35	Xydar, Dart Ind.	Arom. Copoly.
Polyesters	1.50-3.20	7.0	50	40-85	300	1.31	Valox, GE	PBT
Polyesters	1.50-3.20	—	—	40-85	—	—	Rynite, DuPont	PET
Nylon	2.50-3.00	—	—	65-90	—	—	—	—
Polycarbonate	3.50	—	—	127-132	—	—	—	—
Polyphenylene Sulfide	9.30	3800	65	135	—	1.24	Phillips	Ryton
Polysulfone	8.00	3.1	70	150	50-100	1.24	Union Carbide	Polysulfone
Polysulfone	8.00	3.1	70	150	50-100	1.24	LNP Corp.	Polysulfone
Polyether etherketone	50.00	—	—	140-155	—	—	ICI	PEEK
Liq. Crystal Polymers	25.00	—	—	180	—	—	—	—
Polyamides	22.00-35.00	3.3	110	280-360	>300	1.14	DuPont	Zytel Polyamide

Table 4-4: Matrix and Reinforcements vs Processes.

MATRIX / REINFORCEMENT vs PROCESSES								
	Hand Lay-up	Spray-up	Filament Winding	Pultrusion	Resin Transfer Molding	Compression Molding	Injection Molding	Reaction Injection Molding
MATRICES								
Thermoplastics								
— All							*****	
— Polyester PET			*****					
Thermosets								
— Polyester	*****	*****	*****	*****	*****	*****	*****	
— Epoxy	*****	*****	*****	*****		*****	*****	
— Phenolic	*****	*****	*****	*****		*****		
— Polyurethane								*****
— SMC/BMC						*****	*****	
REINFORCEMENTS								
— Continuous Rovings			*****	*****	as preform	preform/SMC		
— Woven Roving	*****			*****	*****			
— Mat	*****			*****	*****			
— Chopped Strands		*****				as BMC		
— Milled Fibres								

4.3 UV Inhibitors

Sunlight has the effect on many plastics of causing discolouration, embrittlement, cracking, chalking, and a loss of mechanical properties. This is due to UV radiation present in sunlight. The UV causes a process known as photoinitiated oxidation, where the chemical bonds are broken by photons of light. The broken chains join with oxygen to form free radicals which cause further chemical deterioration.

Some plastics are inherently more stable to UV radiation due to their chemical composition. For those plastics that are not stable, UV inhibitors can reduce the effects of the radiation. There are several different mechanisms by which UV inhibitors work. One is by absorbing the light energy and transforming it into heat. This type of inhibitor is known as a *quencher*. Other more popular inhibitors are *hindered amines* (HAL). These reduce the number of free radicals, hence reducing the photoinitiated oxidation process. The HAL are considered the most effective means of reducing UV effects.

For many plastics, UV inhibitors can extend the life of the material to make them suitable for buoy applications, and the material life can be expected to meet or exceed the life of steel.

4.4. Impact Strength

Impact strength is a very important factor in the design of a plastic buoy, in particular for the ice spar. Many of the previous attempts at making plastic buoys were criticized for having unacceptable impact resistance. Buoys are exposed to a wide range of impact sources: ice, boat collision, and more commonly, rough handling.

The main mechanisms for absorbing impact are compression, bending, and damping. Compression occurs when a material with a high fracture strain and low modulus has a cushioning effect. Bending occurs when, through proper design, the impacted area is permitted to bend. This is most easily achieved through the use of low moduli materials, but is also effective in carefully designed parts using a high modulus material. If large deflections are not permitted, then the use of ribs or increasing the wall thickness can increase the stress required to cause the same deflections. Damping occurs when the material has sufficient thickness to allow the impact energy to be absorbed internally and dissipated as heat.

There are many factors that influence the impact strength of a material. These include temperature, moduli, and fracture strain. However, for the final impact toughness of the part, the most important factor is the design of that part, and not necessarily the material properties. The factors that must be considered for the design of an impact resistant buoy are the reduction of stress concentrators: notches, sharp corners, grooves, or sudden changes in wall thickness. The use of chopped glass fibre can also reduce the impact strength, as each glass fibre acts as a local stress concentrator.

4.5 Ultimate Strength

For buoys the material used must make it able to resist hydrostatic pressure, wave pressure, mooring loads, lifting loads, ice loads, and superstructure loads. The use of fibre reinforcement can greatly increase the strength and stiffness of plastic materials. Also in current steel buoy design, wall thickness is not based solely on the loads, but also in part on the thickness to be corroded over the life of the buoy With plastic materials corrosion is not a problem so a corrosion margin is not required.

For the spar, can and cone buoys, which do not have a superstructure, the material can have a relatively low strength. However, for the light, bell, and whistle buoys it is important that the material has sufficient strength and stiffness to support the weight and added stress due to the superstructure.

4.6 Moisture Absorption

There are two types of moisture absorption; Fickian, which occurs through the matrix and is driven by a concentration gradient; and non-Fickian, which occurs through micro-cracks and along the fibre-matrix interface. Moisture absorption is greatest with reinforced plastics, as non-Fickian absorption is greater than Fickian absorption, as well, different resins and fibres have different absorptive capacities.

The effect of moisture absorption is a reduction in the fibre-matrix interface, a decrease in the modulus (20-25%) , and increase in Poisson's ratio (5-10%) and an increase in the strain to fracture. The result is that the strength is degraded, but the impact resistance is improved. Therefore, it is necessary for the reduction in strength to be accounted for in the design of a buoy. Another effect of moisture absorption is blistering, which reduces the overall strength of laminated composites. To prevent these effects in reinforced laminated plastics it is necessary to have an extra layer of resin called a "gel coat". The gel coat provides a protective layer between the water and the laminate. For non-reinforced plastics, a gel coat is not required.

4.7 Marine Growth

There is no evidence to indicate a significant difference in fouling with plastics materials. It may be assumed that the same amount of marine growth would occur as with the current buoys. However, it can be noted that the most significant fouling does not occur on the buoy bodies but rather on the bridles and mooring chains, which will still require servicing. Marine growth can be a problem with thermoset resins which usually require a gel coat. The gel coat protects the laminate from moisture, and marine growth may breakdown or cause cracks in the gel coat, thus requiring maintenance to the gel coat (i.e. patching or total replacement in a manner similar to paint removal).

4.8 Colour Stability

An important function of navigational buoys is to act as a visual marker that provides information through its colour. Although many resins have there own colour, the usual method for achieving a particular colour is through the use of colourants.

Colourants come in two forms, either as a pigment, or as a dye. A pigment is a finely powdered material that is dispersed in the resin. Pigments can be either organic or inorganic. The inorganic pigments are more stable and less likely to fade. Dyes, unlike pigments, are dissolved into the resin. The major limitations with dyes are that they are not compatible with many resins, and they have poor fade resistance. The UV stabilizers used with many plastics usually only protect the resin, and they do not prevent the fading of colour. However, most pigments have good colour stability and do not require the protection of the UV stabilizers.

When considering a colourant the processing method must also be considered. Many processes can have a detrimental affect on a colourant if they are not properly matched. Processes with long heating cycles can cause " heat failure" in some colourants, and "shear heat" can cause a similar colourant failure.

5. MANUFACTURING PROCESSES

5.1 Processes Related to the Manufacture of Buoys

For the manufacture of buoys there are several criteria which must be examined. These include shape and size factors, performance requirements, and economic factors. Each manufacturing process places certain limitations on the shape and size of the products that they can produce. Many processes can not produce a hollow hull, which would make them unsuited for the manufacture of buoys. Some of the processes can only manufacture parts up to a certain size, which would limit the type of buoys that can be made. The performance requirements include strength, stiffness, strain to failure. These requirements are determined by the type of buoy. Some buoys are required to support a superstructure; others are required to withstand significant ice impact loading; all of them are required to withstand mooring, lifting, and incidental impact loading. The ability to meet these requirements is partially related to the types of resin and reinforcement that can be used with a particular manufacturing method and by the actual design of the part. The economic factors are related to the volume of production, the start-up costs, indirect and direct labour costs, production costs, and material costs.

For each of the buoys, several manufacturing processes were evaluated. The processes that are given are those that meet the shape and size factors, as well as the performance requirements. Due to the wide variability in performance requirements and shape and design factors, some processes will only be suited for a particular type of buoy. Also, a particular process may only be economically viable for relatively large production runs. This has been considered and mentioned where applicable.

5.1.1 Ottawa River Spar

The Ottawa River Spar has a relatively short and narrow buoy hull. It is usually located in protected waters. It does not have a superstructure, nor does it support a light. Therefore it does not require a particularly strong hull, and reinforcement should not be a requirement. These factors led us to examine the possibility of manufacturing the Ottawa River Spar using several processes, these included: filament winding, rotational molding, blow molding, and extrusion.

Filament winding has an advantage in that it permits the use of continuous fibres and a high fibre content. An Ottawa River Spar filament wound, would have a thinner hull, resulting in a lighter buoy. For additional strength the attachment for the mooring and the lifting eye would be wound into the structure of the buoy.

Rotational molding can be used for manufacturing Ottawa River Spars. This method is most economical for medium scale production. The resulting buoy would be heavier than a filament wound buoy due to the lack of reinforcement. But, as in filament winding, the metal attachments can be molded into the buoy.

Blow molding is another method which may be used for manufacturing Ottawa River Spars. However, this method only becomes economical for large volume production, mostly due to the relatively high cost for tooling. Another disadvantage of this method is that the metal attachments can not be molded into the structure of the buoy. This would result in a possible weak point, and in extra labour for attaching the parts.

Extrusion produces parts which have a constant cross section. Since the traditional Ottawa River Spar does not have a constant cross section, an extruded Ottawa River Spar would

require a different configuration. An extruded Ottawa River Spar would be a cylinder, and it may be possible to use the die from an existing pipe for prototype manufacturing.

5.1.2 Can/Cone Buoy

Can and cone buoys range in size from 0.8 m diameter to 2.0 m diameter. They are not required to support a superstructure, and therefore do not have a significant strength requirement. The manufacturing processes that can fabricate a can or cone buoy include filament winding, rotational molding, and for the smaller buoys, blow molding.

A filament wound can or cone buoy would have a thinner hull, which would result in a lighter buoy. The mooring attachment and the lifting eye can be wound into the structure, for greater strength.

A rotational molded can buoy would require a thicker hull than a filament wound buoy. However, there are many rotationally molded products that already have a configuration similar to the can buoy, such as large drums and water tanks. This would eliminate the cost of tooling, thus reducing the cost of the buoy.

Blow molding has much the same advantages and limitations as rotational molding. As with rotational molding there are existing products such as drums which might be modified to be used as can buoys. An advantage over rotational molding is its economic viability for larger volumes of production.

5.1.3 Spar Buoy

Spar buoys are very long and slender. They are used in a wide variety of locations and environments. Spar buoys are not required to carry a superstructure, but are sometimes required to support a light and its batteries. Ice spar buoys are required to be particularly robust to withstand impact from ice and the crushing forces of ice jams. Ice spar would be expected to be designed to withstand large hull displacements without failure.

Filament winding offers an advantage of having greater strength and, depending on the matrix-reinforcement combination, this method could also produce a buoy with a high strain to failure.

Extrusion lends itself very well to the manufacture of spar buoys. Their constant cross section makes it possible to fabricate a spar buoy using dies for existing pipe, thus eliminating the cost of tooling. The walls would be thicker than with filament winding due to the lack of reinforcement. The initial start-up costs would be greater, however, due to the longer set-up time than with filament winding. But once the machine has been set-up, it operates as a continuous process. So, depending on the volume of production extrusion may be less expensive than filament winding.

5.1.4 Light Buoy

Light buoys are required to carry a superstructure, therefore the hull of the buoy requires greater stiffness and strength. The increased stiffness may be achieved by increasing the wall thickness, using reinforcement, or by using stiffeners. The relatively large size, and the configuration of the light buoy does not lend itself to as many manufacturing processes. The processes that could best manufacture a light buoy are filament winding and rotational molding.

The advantage of using filament winding is that the resulting hull would have a high strength and stiffness for a relatively thin laminate. The metal attachments for the mooring line and lifting eyes could be wound into the structure.

The size and configuration of the light buoy are within the limitations of rotational molding. In order to achieve the necessary strength and stiffness the hull would have to use a relatively thick wall. This would result in increased material, increased weight, and increased processing time. The cost of tooling the mold for a light buoy would be significant.

5.1.5 Light and Sound Buoys

The light and sound buoys have very high load requirements on the deck of the buoy due to the weight of a superstructure, light, and either a bell or a whistle. So, the hull of the buoy must be very strong and have a high stiffness. In this case the use of reinforcement would be an advantage.

Due to the size, configuration, and strength requirements, filament winding offers the best solution for manufacturing light and sound buoys. It has the ability to mold the buoy bodies in a single piece, which would reduce stress concentrations It can provide sufficient strength when using the appropriate matrix reinforcement combination. All the metal attachments for mooring and lifting could be wound in , as well as the supports for the battery packs.

5.1.6 Superstructure

The light and the light and sound buoys can all be designed to support existing superstructures. However, using an existing superstructure would limit the service time interval, as they would be subject to corrosion. A better alternative would be to fabricate a superstructure from pultruded sections. This would result in a lighter and corrosion resistant superstructure which would not limit the service interval. A major concern with using pultruded sections is joining and fastening. However, a properly designed superstructure should be able to meet the performance requirements.

5.2 Overview of Manufacturing Techniques

The following represent the major plastics manufacturing processes: injection molding, compression molding, transfer molding, reaction injection molding, resin transfer molding, blow molding, rotational molding, thermoforming, filament winding, open mold (hand lay-up), and pultrusion.

5.2.1 Injection Molding

Injection molding is a process in which a fast reacting resin is melted (thermoplastics) or heated (thermoset), then injected in to a mold and held at high pressure (700 MPa - 2100 MPa) until the part has solidified. Due to the high pressures the molds are made of a high strength steel. The tooling cost for the molds is therefore very expensive - for example, a small simple mold is approximately $62 000.

The advantages for injection molding are: high rate of production, a broad range of resins, a high degree of dimensional accuracy, and a superior finish. For these reasons injection molding is used extensively in the automotive industry.

The main disadvantage of injection molding is its high tooling and capital equipment costs. For the production of buoys this method would be prohibitively expensive. Another disadvantage is its limitation on the size of products which can be molded. This limitation is due to the high clamping forces required to maintain the high pressures. In recent years injection molding machines have been introduced which are capable of producing larger products. However, the largest machine is still limited to products that are less than 1 m^3 in size. Another problem created by the high pressures is the creation of molded-in stress. This can lead to a reduction in the ultimate strength and the creation of stress cracking.

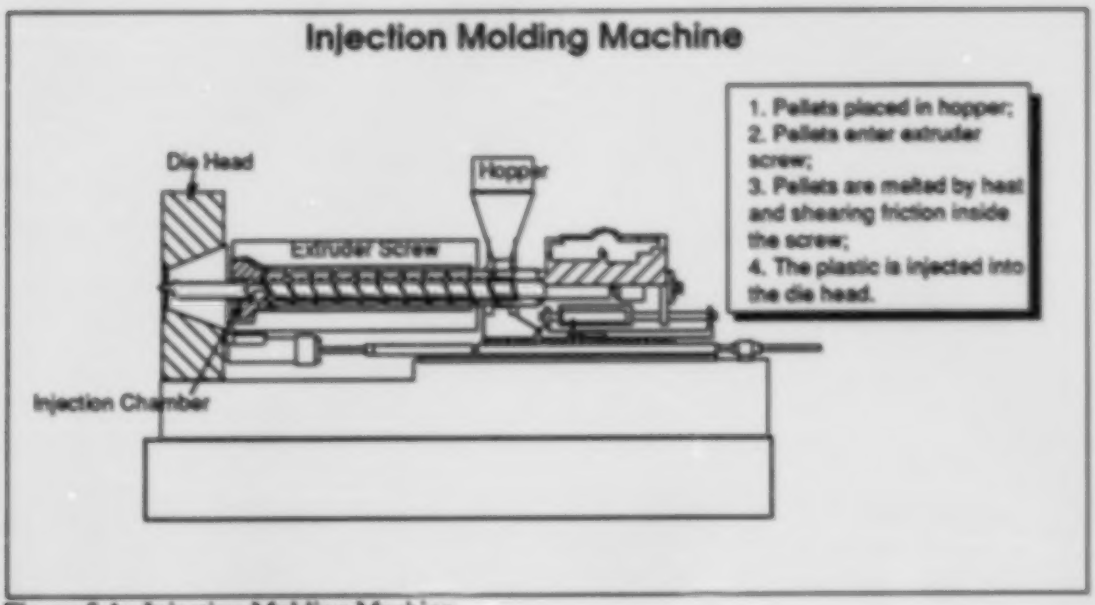

Injection Molding Machine
1. Pellets placed in hopper;
2. Pellets enter extruder screw;
3. Pellets are melted by heat and shearing friction inside the screw;
4. The plastic is injected into the die head.
Die Head
Hopper
Extruder Screw
Injection Chamber

Figure 5-1: Injection Molding Machine

5.2.2 Compression Molding

Compression molding is a process in which a charge of resin is placed on the female side of a fixed mold, then both sides of the mold are heated and pressed together. The resin then flows to take the shape of the mold. The pressures generated by compression molding are between 180 kN and 9 MN, depending on the size of the mold. The resins used can be either thermoplastic or thermoset. The thermoset resins are usually used in the form of pre-combined composite, such as a bulk molding compound (BMC), or a sheet molding compound (SMC). A sheet molding compound is a reinforcing mat that is preimpregnated with a resin and a catalyst, and is cut into suitable sized sheets. The most typical application of compression molding is for molding parts that are too large for injection molding.

The advantages of compression molding include: high rate of production, large parts, accurate dimensions, and controlled fibre placement. The tooling costs are typically 80% of injection molding. For short production runs, the mold can be made of less expensive material, further reducing their cost

There are several disadvantages to compression molding:

- It is incapable of producing single piece hollow parts.
- It is difficult to use metal inserts, due to their tendency to have their alignment distorted during the pressing process.
- Although less expensive than injection molding the tooling costs are relatively high.
- The maximum size of a product is limited by the size of the press which is typically less than 2 m^2.

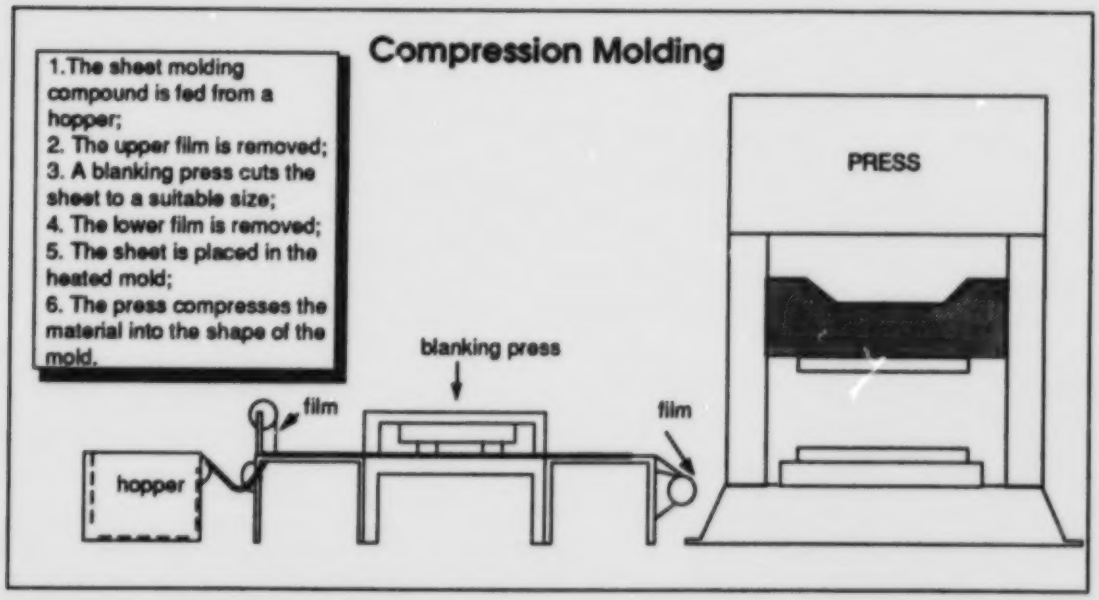

Compression Molding
1.The sheet molding compound is fed from a hopper;
2. The upper film is removed;
3. A blanking press cuts the sheet to a suitable size;
4. The lower film is removed;
5. The sheet is placed in the heated mold;
6. The press compresses the material into the shape of the mold.
PRESS
blanking press
film
film
hopper

Figure 5-2: Compression Molding

5.2.3 Transfer Molding

Transfer molding is a process in which a charge of pre-heated thermoset resin is placed in an auxiliary chamber, called the pot, then a piston forces the charge out of the pot and into the mold, where polymerization (curing) takes place. This process is used primarily for small intricate parts such as pot handles, and hand held tool housings.

The advantages of transfer molding are high production rates and the ability to mold in inserts. This process is often used instead of compression molding when molding small parts. Its cycle times are quicker, and the final product requires less finishing than with compression molding.

The major disadvantage of transfer molding is it size limitations. This process can only be used to manufacture very small parts.

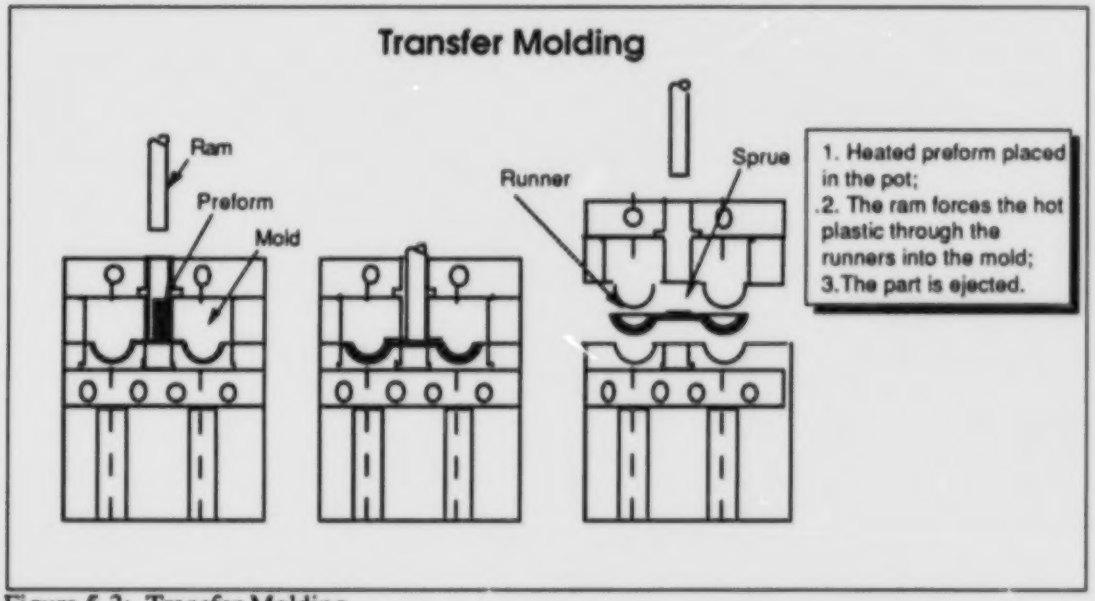


Figure 5-3: Transfer Molding

5.2.4 Reaction Injection Molding and Resin Transfer Molding

Reaction injection molding and resin transfer molding are similar processes. They use similar equipment and have similar advantages and disadvantages. For this reason they have been grouped together for this discussion. These processes require a resin or resin components to be injected into a mold where they mix and polymerize. For RIM two monomers are injected, and for RTM a resin and a catalyst are injected. Reinforcing material is often placed in the mold to produce high strength parts. Wall thickness up to 40 mm have been achieved, and like injection molding, the surface finish duplicates the mold very accurately.

There are several advantages to using RIM/RTM:

- The resins are less viscous and are able to flow more freely than with injection molding. The result is lower pressures (0.345 - 34.5 MPa), temperatures (24 - 50°C), and the ability to mold large products.
- The molds can be made of less expensive material, and are typically one-third the cost of an injection mold. As a comparison, an automotive bumper requires typically between 900 and 1300 kN of clamping force, but for a comparable injection molded part, 31 000 kN of clamping force would be required.
- For mid-volume production of between 4000 and 25 000 units, they offer a cost advantage over compression or injection molding, and faster production than with hand lay-up.
- RIM/RTM offer superior strength to injection molding due to controlled fibre placement.
- It has less molded-in stress than injection molding, due to the low pressures during curing.

There are few disadvantages to the use of RIM/RTM. One is the inability to mold single piece hollow parts. Another, is the relatively expensive process, which has an advantage over hand lay-up only on production runs of more than 4000 units.

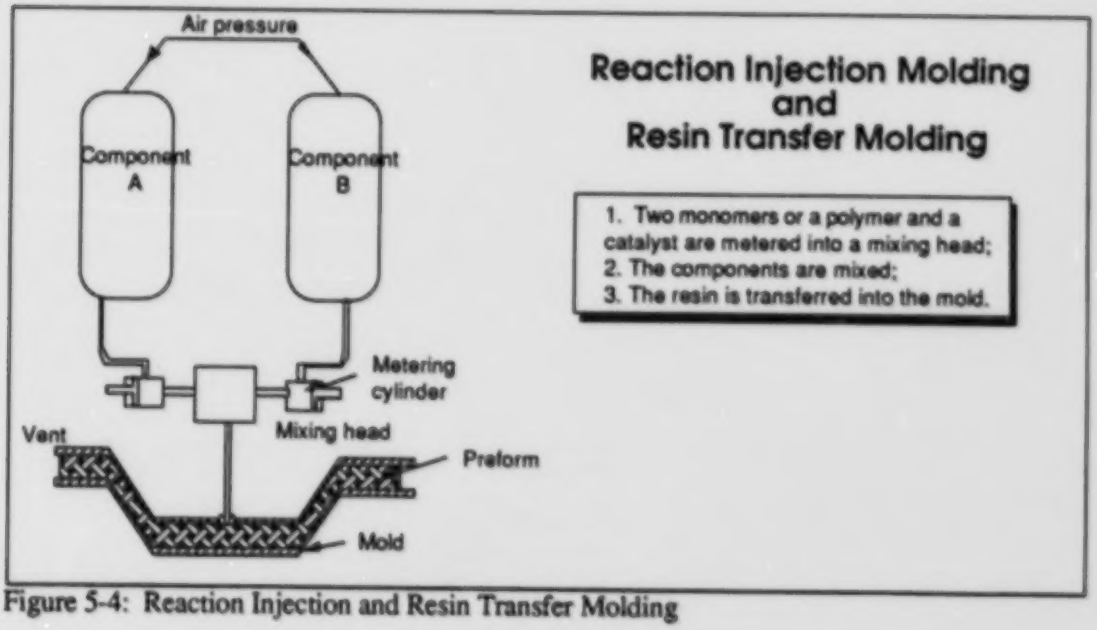

Air pressure
Component A
Component B
Metering cylinder
Mixing head
Vent
Preform
Mold
Reaction Injection Molding and Resin Transfer Molding
1. Two monomers or a polymer and a catalyst are metered into a mixing head;
2. The components are mixed;
3. The resin is transferred into the mold.

Figure 5-4: Reaction Injection and Resin Transfer Molding

5.2.5 Blow Molding

There are several stages to the blow molding process:

- A parison (a round hollow tube) of molten plastic is extruded into an accumulator head.
- The accumulator head holds the extruded plastic and forms a die head through which the plastic is ejected.
- The parison is trapped between two halves of the mold.
- The parison is then expanded with air pressure (usually 690 kPa) against the cavity of the mold to form the part.
- The part is cooled, removed from the mold, and the excess trimmed.

Blow moldings is a fast efficient means of creating hollow shapes. It has rapid cycle times and requires very little manual labour. For these reasons it is used extensively for the manufacture of bottles, drums, and gas tanks.

There are several disadvantages to the use of blow molding:

- There is a limitation on the size of the product that can be manufactured. The largest product blow molded is an 800 litre drum, however, the sizes are usually less than 200 litres.
- The wall thickness is limited to less than 5 mm.
- Reinforcement can not be used.
- Only thermoplastics can be used with this process.
- Blow molding requires machined metal molds, which are expensive to produce. Although cheaper than injection molding, the molds are three times more expensive than for rotational molding.
- Metal inserts cannot be molded into the products.

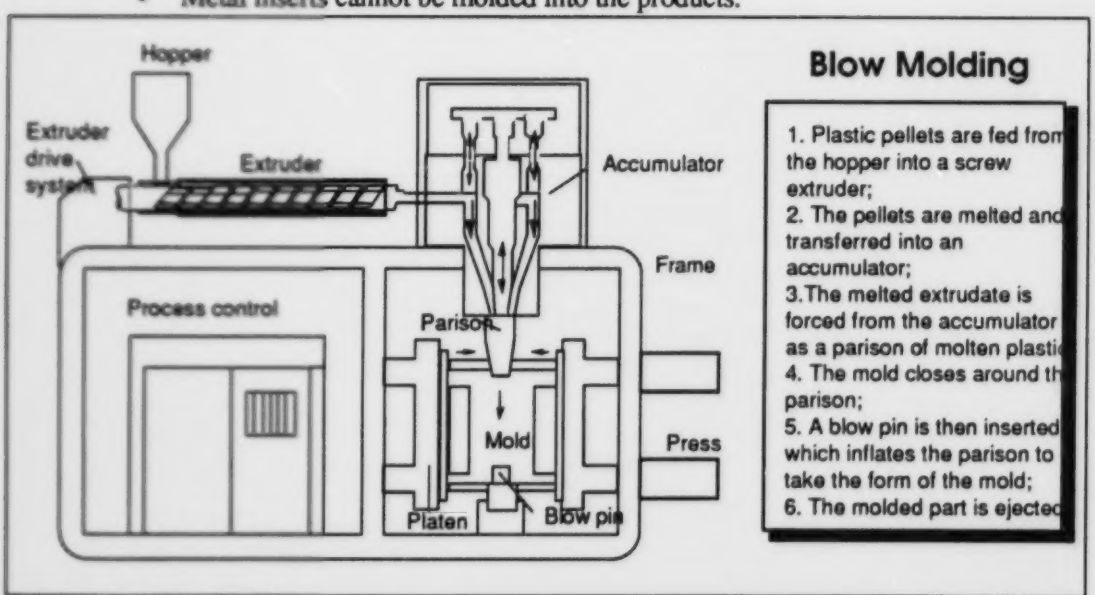

Blow Molding
Hopper
Extruder drive system
Extruder
Accumulator
Frame
Process control
Parison
Mold
Press
Platen
Blow pin
1. Plastic pellets are fed from the hopper into a screw extruder;
2. The pellets are melted and transferred into an accumulator;
3.The melted extrudate is forced from the accumulator as a parison of molten plasti
4. The mold closes around th parison;
5. A blow pin is then inserted which inflates the parison to take the form of the mold;
6. The molded part is ejected

Figure 5-5: Blow Molding

5.2.6 Rotational Molding

Rotational molding is a four stage process. (1) a powdered plastic is placed into a mold, (2) the mold is rotated and heated allowing the molten plastic to coat the inside of the mold, (3) the mold continues to rotate while it is cooled by air or intermittent water jets, (4) the part is removed from the mold. Rotational molding is used extensively for the manufacture of large hollow products, and it competes primarily with blow molding for many applications.

There are several advantages to rotational molding:

- It can produce large single piece hollow products. Products as large as a 10 000 litre water tanks are rotomolded.
- The wall thickness can be made very thick, up to 25 mm. The thickness can be adjusted by simply adding more plastic, no additional tooling necessary. Also the wall thickness is more uniform than with blow molding.
- Metal inserts can be molded directly into the product. This decreases the amount of additional assembly required.
- The products are molded virtually stress free, since pressure is not used in the process.
- The cost of the mold is one third the cost of a similar blow or injection mold, making it very competitive with blow molding on small production runs. Overall, the cost of the equipment is low compared to the production capability.

There are few disadvantages with rotational molding. One of them is the difficulty in using reinforcement. Only chopped fibre can be used and it is difficult to control the fibre distribution. Another disadvantage is, when compared to compression, RIM/RTM, or blow molding, rotational molding is a slow process.

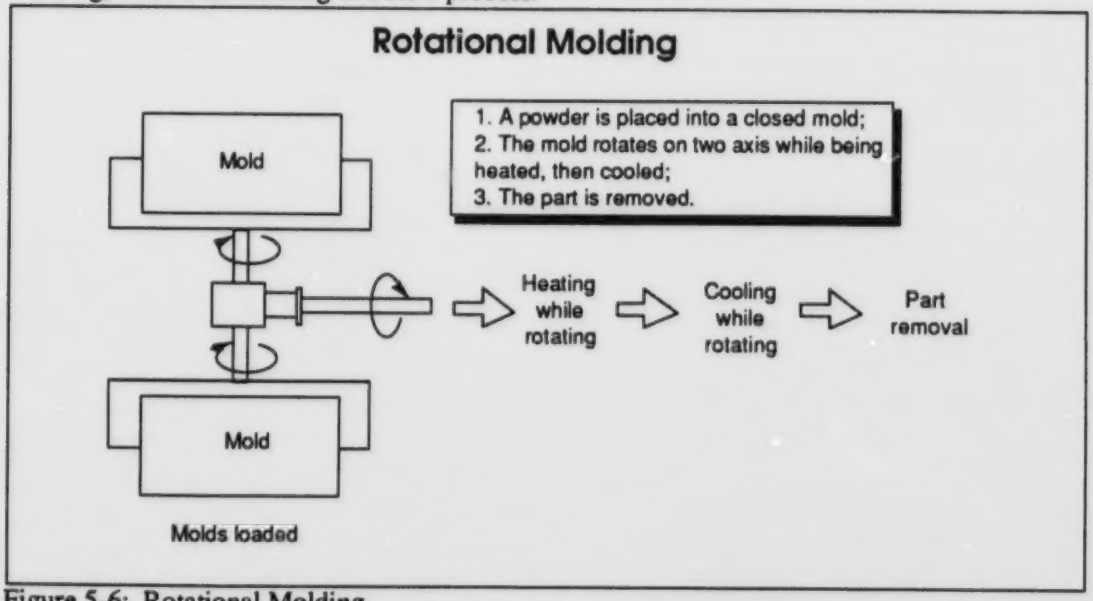

Rotational Molding
1. A powder is placed into a closed mold;
2. The mold rotates on two axis while being heated, then cooled;
3. The part is removed.
Mold
Heating while rotating
Cooling while rotating
Part removal
Mold
Molds loaded

Figure 5-6: Rotational Molding

5.2.7 Thermoforming

Thermoforming is a process in which a sheet of plastic is placed over a mold, and is heated until it is soft. A vacuum is then applied which draws the plastic to the side of the mold. Thermoforming is often used in the production of trays and cups, but has also been used for manufacturing canoes. Twin sheet forming, a variation of thermoforming, is used to create large flat hollow panel structures.

Thermoforming's advantages are due to the relatively inexpensive technology required. It is one of the oldest methods used for the forming of thermoplastics. And since it is a low pressure process, the molds can be made from very inexpensive materials.

Thermoforming introduces certain limitations to the design of a product:

- The wall thickness is determined by the thickness of the plastic sheet used and by the depth of draw. Typically a thick sheet is 5 mm thick, thus limiting the wall thickness to less than 5 mm.
- Reinforcement cannot be used with thermoforming.
- This method cannot form a single piece hollow part except for flat panel-like structures.

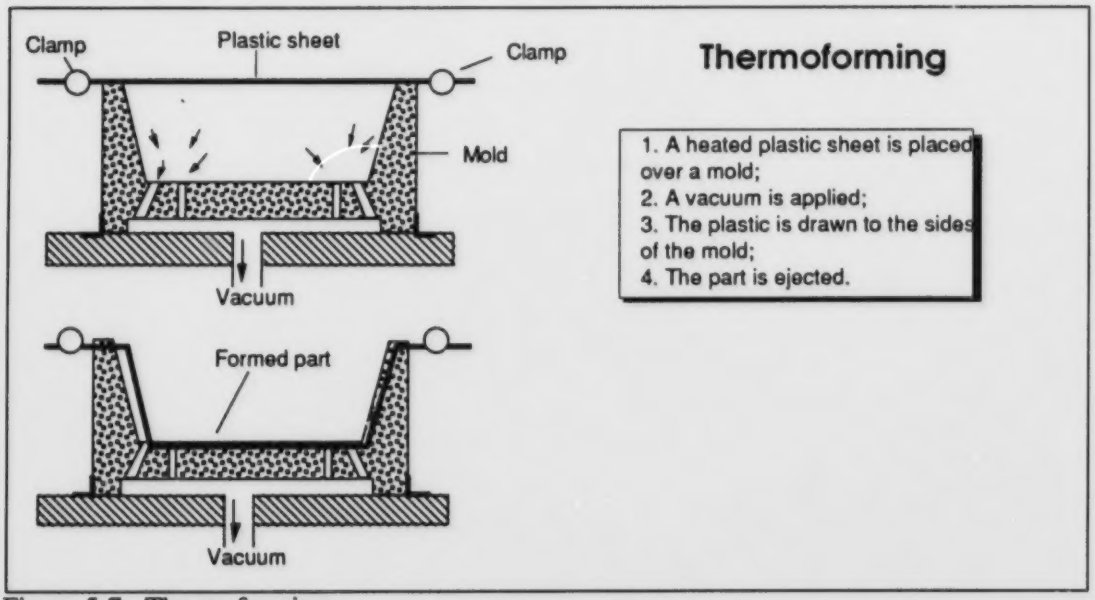


Figure 5-7: Thermoforming

5.2.8 Filament Winding

Filament winding is an automated method of creating reinforced plastic parts. In its simplest form it involves a mandrel that is rotated and a head that directs the fibres along a path around the mandrel. In this way, pipes and large hollow parts such as pressure vessels are manufactured. Normally the part will have a certain degree of symmetry along an axis. Today's computer controlled filament winders can wind more complex shapes, but it is still dependent on a stable fibre path.

Filament winding has several advantages over other manufacturing methods:

- Filament wound parts are very strong due to the controlled fibre alignment and the use of continuous fibres.
- Metal inserts can be wound into the structure.
- Thermoset and thermoplastics can be filament wound.
- Since it is an automated process it is much quicker than hand lay-up for similar parts.

There are some disadvantages to filament winding when compared to other manufacturing processes:

- It is slower than many of the other methods.
- It is limited in the complexity of the shapes that can be formed, due to the fibre path requirements.

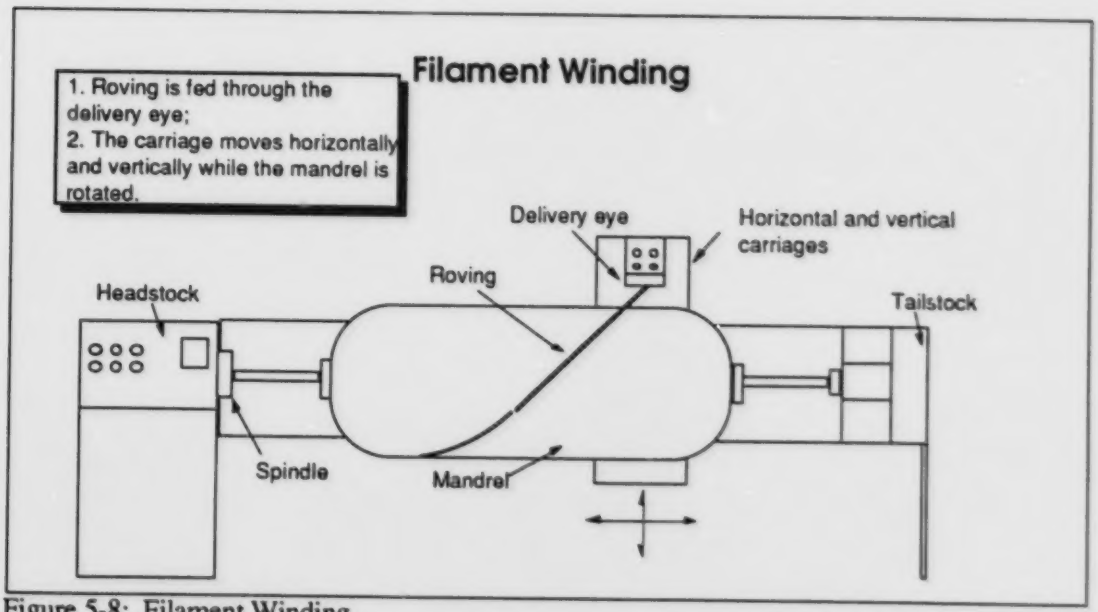


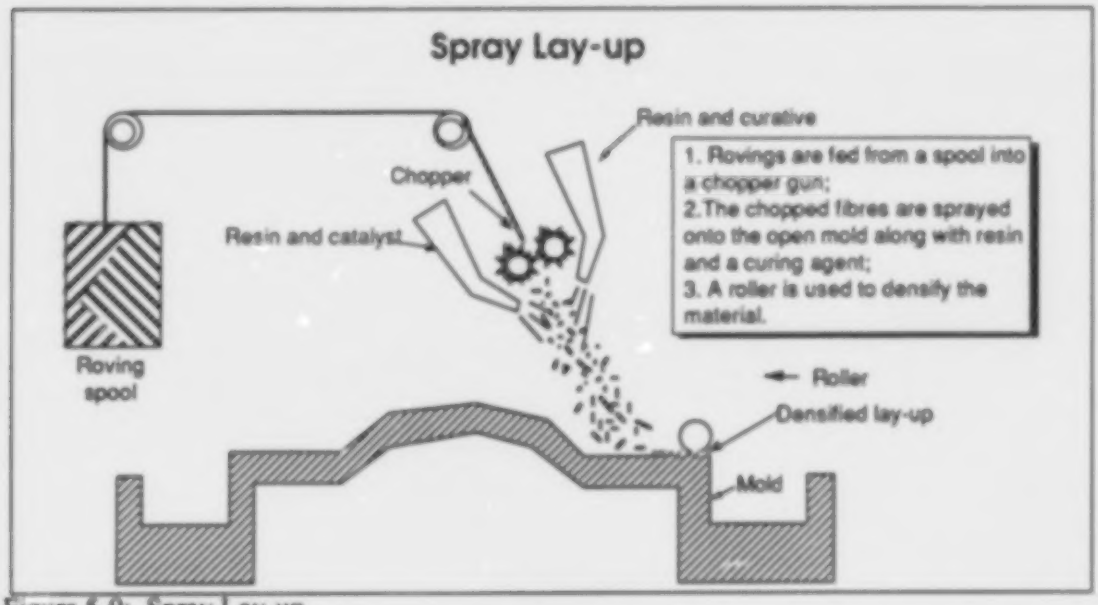
Figure 5-8: Filament Winding

5.2.9 Open Mold (Hand Lay-up)

Open mold includes hand lay-up and spray lay-up. For hand lay-up the resin wetted fibres are laid down on the surface of the mold. For spray lay-up a special gun sprays chopped fibre and resin on to the mold surface. Both these applications require pressure to be applied to the surface, once laid-up, while the resin cures. These methods use low technology, and are an inexpensive means of construction. The equipment costs under $10,000. There are no practical limits to the size and complexity of the mold.

The advantages of open mold are: inexpensive equipment, no practical limit to size and complexity, controlled fibre placement, and the ability to mold in metal inserts. The equipment is readily available to many small manufacturers, as it is the same equipment used for making fibre glass boats, and pick-up truck caps.

The disadvantage of open mold processing is that it is a labour intensive process. This means that it is slower than the other processes. Also, the labour cost is a significant portion of the final product cost.


Spray Lay-up
Resin and curative
Chopper
Resin and catalyst
1. Rovings are fed from a spool into a chopper gun;
2.The chopped fibres are sprayed onto the open mold along with resin and a curing agent;
3. A roller is used to densify the material.
Roving spool
Roller
Densified lay-up
Mold
Figure 5-9: Spray Lay-up

5.2.10 Extrusion

The process of continuous extrusion involves the melting of thermoplastic pellets inside an extruder and forcing the melted plastic through a die head to form the final shape of the extrudate. The extruder is nothing more than a screw type conveyor that melts plastic through shearing friction and heat from external heaters. Once the plastic has passed through the die head it is normally cooled by water immersion, a cold water spray, or by air cooling.

Thermoplastic extrusions are currently being used for the fabrication of ice spar buoys. In this case an existing polyethylene pipe has been modified by the addition of end caps and mounting brackets for batteries and a light fixture. This would seem to be an economical method for producing these lighted ice spars; however these buoys are prohibitively expensive.

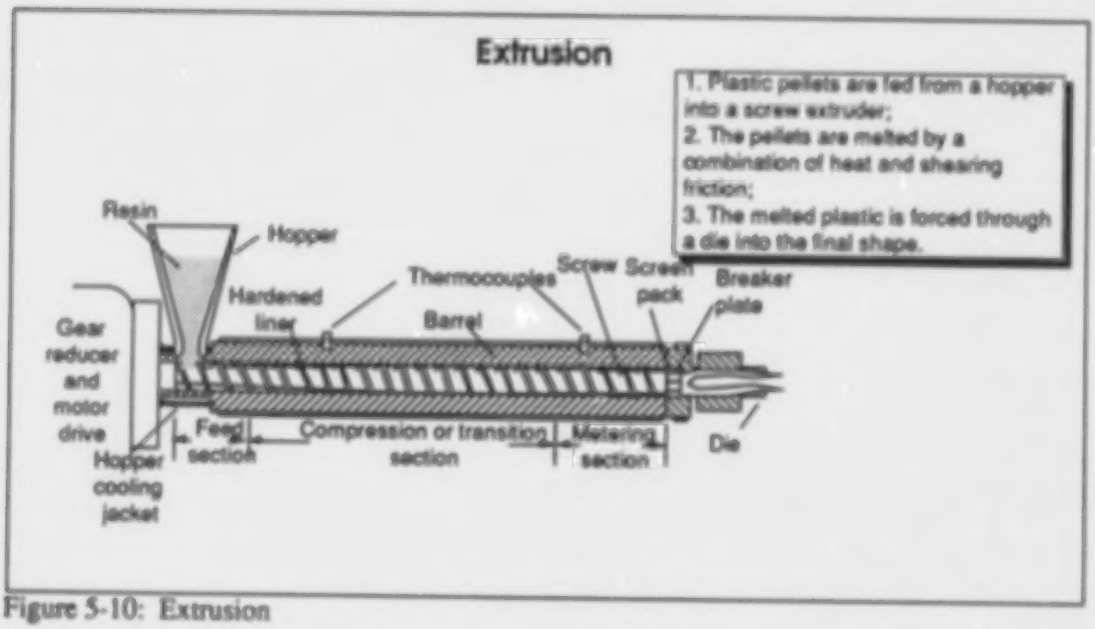


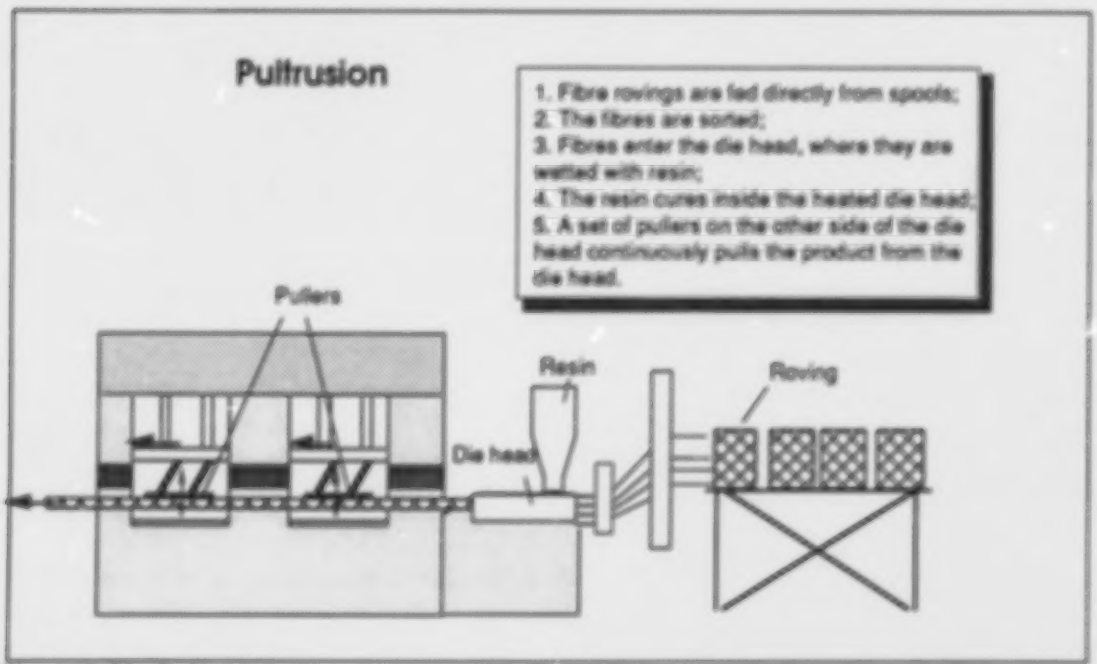
Figure 5-10: Extrusion

5.2.11 Pultrusion

Pultrusion is an automated method for creating reinforced plastic parts of constant cross-section. In this process fibres are fed from a fibre dispenser. The fibres proceed through a bath where they are impregnated with resin. The wetted fibres then travel through a pre-shaping unit and into a heated die where the resin is cured. A puller on the other side of the die pulls the product from the end of the heated die. The product cools in the ambient air and is cut-off at the desired lengths.

The advantage of pultrusion is that it is the most cost effective way of producing plastic fibre reinforced products of constant cross section. It is highly automated process with a continuous and rapid output.

The disadvantage with pultrusion is that it is limited to constant cross section products. The size is determined by the clamping force of the pullers and the frictional force of the die.


Pultrusion
1. Fibre rovings are fed directly from spools;
2. The fibres are sorted;
3. Fibres enter the die head, where they are wetted with resin;
4. The resin cures inside the heated die head;
5. A set of pullers on the other side of the die head continuously pulls the product from the die head.
Pullers
Resin
Roving
Die head
Figure 5-11: Pultrusion

Process	Key Advantages	Notable Limitations
1. Injection Molding	1. High rate of production. 2. Can use chopped fibre reinforcement. 3. Wide range of available resins.	1. Very high tooling costs make this method prohibitively expensive for buoy manufacture. 2. Does not mold single piece hollow parts.
2. Compression Molding	1. High rate of production. 2. Can use mat reinforcement.	1. Very high tooling costs make this method prohibitively expensive for buoy manufacture. 2. Does not mold single piece hollow parts.
3. Transfer Molding	1. High rate of production. 2. Good for small intricate parts.	1. Can only mold small parts.
4. RIM/RTM	1. Moderate rate of production, between spray-up and the faster, compression molding.	1. Cannot mold single piece hollow parts.
5. Blow Molding	1. Mold single piece hollow parts. 2. High rate of production.	1. High tooling cost. 2. No fibre reinforcement. 3. Maximum size limited. 4. Limited to thermoplastic resins.
6. Rotational Molding	1. Mold single piece hollow parts. 2. More cost effective than blow molding, for small production runs. 3. Can use some reinforcement, with limitations. 4. Lower tooling costs than blow molding.	1. Moderate tooling cost.
7. Thermoforming	1. Can mold large parts. 2. Equipment is relatively inexpensive.	1. Cannot use reinforcement. 2. Maximum wall thickness limited to less than 5 mm.
8. Filament Winding	1. Can wind large parts. 2. Very strong due to oriented fibre placement. 3. Can create hollow parts.	1. Limited part complexity due to stable fibre path requirements.
9. Hand Lay-up/ Spray-up	1. Inexpensive equipment. 2. No size or complexity constraints.	1. Limited to thermoset resins.
10. Pultrusion	1. Very strong parts due to oriented fibre placement. 2. High rate of production.	1. Part configuration limited to constant cross section.
11. Extrusion	1. Can produce hollow cross section parts. 2. High rate of production.	1. No fibre reinforcement.

Table 5-1: Key Advantages and Limitations of Different Manufacturing Processes

6. DETAILED ANALYSIS

The verification of concept involved a first iteration detailed analysis of an ice spar and a bell buoy. It was assumed that the material used for the analysis would be an E-glass epoxy laminate and the means of construction by filament winding. The analysis was performed in three steps, (1) the buoy loadings were calculated and a preliminary laminate thickness was determined, (2) a stability analysis was performed, (3) a finite element analysis was performed. After each step the model was refined in an attempt to optimize the design.

This is only a first iteration detailed analysis. Several iterations of the design procedure would be required to achieve a final design suitable for fabrication and service. Therefore, the results should only be used as a baseline for a comparison with conventional buoys. Since plastics and composites represent a new material for the design of buoys, many of the conventional design assumptions do not apply. As well, with plastics and composites, the designer is not only designing the product, but must also design the material. Therefore, any practical design would require a more detailed analysis than with conventional buoys.

6.1 Preliminary Design

The Navigational Buoy Design Manual[1] provides a guideline for the calculation of loadings and for the design of buoys. Since the material being used is different from the traditional material, primarily steel, this manual was used only for determining loadings. The loads that were considered were: hydrostatic pressure; wind, wave, current loads; lifting loads; mooring loads; ice loads; and superstructure loads. Impact loading was ignored for this phase of the design process. However, an attempt was made to determine ice impact loading for the ice spar buoy only.

Table 6-1 shows the initial conditions which were assumed in the design calculations. From these conditions a set of preliminary loads were determined as in table 6-2. It was assumed that there was no ice loading for the bell buoy, as these are replaced by ice spars in the winter months.

INITIAL CONDITIONS		
	SPAR	BELL
Water line	4.82 m	2.373 m
Freeboard	4.65 m	
Wave Ht.	6.0 m	13 m
Wave period	5 sec.	10 sec.
Wind velocity	18 m/s	31 m/s
Current velocity	2 m/s	3.1 m/s

Table 6-1: Initial Conditions

[1] Navigational Buoy Design Manual, Canadian Coast Guard, Aids and Waterways

SUMMARY OF FORCES		
	SPAR(ice condition)	BELL(no ice)
Buoy mass	2950 kg	2570 kg
Superstructure load	0.794 kN	0.0384 kN
Current Force	4.141 kN	7.112 kN
Wind Force	0.287 kN	1.377 kN
Wave load	7.354 kN	5.731 kN
Breaking wave load	184 kN	103 kN
Mooring cable force	5.750 kN	11.86 kN

Table 6-2: Summary of Forces

Once the loads had been calculated it was then possible to determine a preliminary laminate thickness and configuration. Due to the anisotropic nature of composite materials the formulas for stress and strain of isotropic materials do not apply. Hence, specialized software was used to estimate the number of plies, their direction, and the thickness of the laminate. This software is designed for use with a very specific set of geometries and loading conditions, so it is therefore not suitable for a detailed analysis, but it does provide an approximation from which further design refinement can proceed. For the analysis of the ice spar a simple pressure vessel was used as the approximate buoy geometry, and a uniform external pressure was applied as an approximation of the loading conditions. This allowed us to choose a suitable laminate for this condition which could then be used in the further analysis of the bell and ice spar buoys.

6.2 Stability Analysis

The stability of a buoy is the result of a balance between several forces including: mooring loads, ice accretion, wind, and wave loads. All navigational buoys are required to meet minimum stability criteria. These criteria are outlined in the "Navigational Buoy Design Manual" and vary depending on the type of buoy and its operational environment.

The stability analysis was performed on both the ice spar and the bell buoy. The ice spar was examined for ice and no ice conditions, the bell buoy was only examined for the no ice condition. The results of the analysis along with the minimum requirements are given in table 6-3. Figures 6-1 to 6-3 show the stability curves of the buoys.

	GM (m)	qm	qx	qr	Gzw/Gzwmax
Min. Req'd					
Ice Spar	0.15	15°	45°	90°	0.40
Lighted	0.15	18°	30°	90°	0.60
Results					
Ice Spar	1.636	16.5°	90°	>90°	0.135
Lighted	0.583	6°	90°	>90°	0.02

Table 6-3: Minimum required stability and calculated stability for the composite buoys

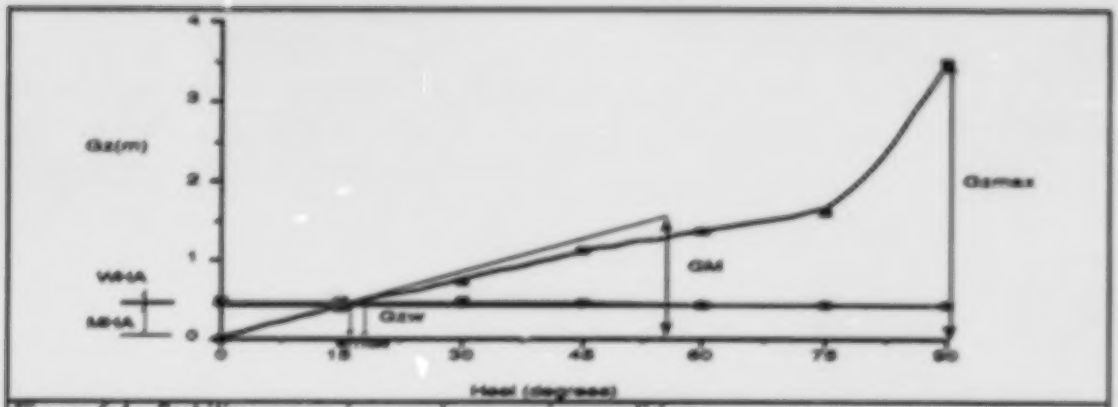


Figure 6-1: Stability curve: ice spar buoy, no ice condition.

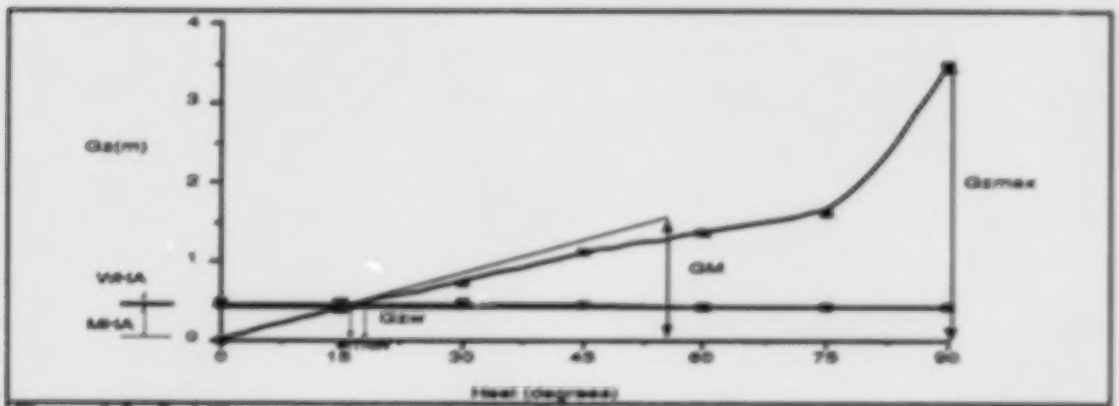


Figure 6-2: Stability curve: ice spar, ice condition.

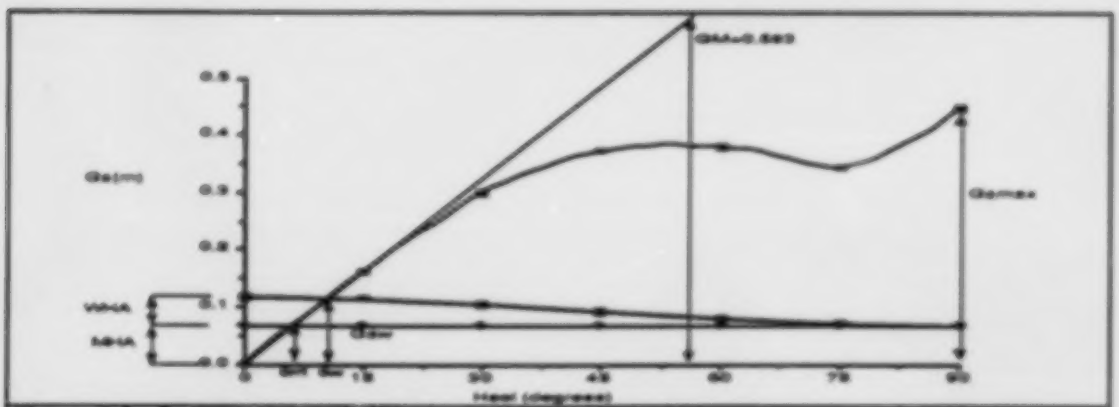


Figure 6-3: Stability curve: bell buoy, no ice condition

Given our initial assumptions our stability analysis indicates that the bell buoy does not meet the minimum required stability criteria. Subsequent iterations of the design process would have to consider widening the buoy hull or using baffles to dampen the buoy's motion. The ice spar, however, does meet the minimum stability requirements on this first iteration. Subsequent iterations could improve this buoy's response.

6.3 Finite Element Analysis

Finite element analysis (FEA) provides an accurate means of determining the strength of a structure under a variety of loading conditions. For reinforced plastics, which exhibit different properties in different directions, finite element analysis may provide the only attainable solution. This is possible by discretizing the structure into a number of smaller structures of simple geometry called elements. For each of these elements there exists an algebraic equation that describes the element's behavior under various loading and boundary conditions. A computer can then be used to solve these equations simultaneously to provide an approximation of the overall model behavior.

An important consideration in FEA is the choice of an element that best approximates the behavior of the material being modelled. For this analysis a "composite" element was used. Composite elements are available in only a few FEA programs such as the one used here, Algor. This composite element takes into account the directional characteristics of reinforced plastics, as well as the interaction between various layers of the laminate.

The loadings that were used for the FEA analysis of the buoy were hydrostatic, mooring, super-structure, and breaking wave loads. The purpose of this analysis was to determine whether a reasonable wall thickness can be manufactured to withstand these loadings . It was not assumed that this analysis would be used as a detailed design analysis. For this reason a safety factor was included to account for other types of loadings, including impact.

The FEA model of the ice spar modelled one half of the buoy due to the symmetry inherent in the model. FEA analysis permits the simplifying of a model where there is symmetry in both loading and boundary conditions. For the first analysis stiffeners were placed in the model, as is the practice for conventional spar buoys. The analysis indicated that the buoy structure was stronger than anticipated, so another analysis was performed without the stiffeners. This analysis indicated that even without stiffeners the buoy's structure was strong enough for the loading conditions.

The FEA model of the bell buoy modelled one quarter of the buoy due to the symmetry of the loading and boundary conditions on two planes. The analysis indicated that the structure was strong enough for the current set of loading conditions. It also indicated areas where the wall thickness could be reduced, and areas where it may be reinforced. Depending on the manufacturing process this could result in a significant reduction in material, manufacturing time, and could also reduce the buoy's weight.

7. CONCEPTUAL DESIGNS

Five buoys were evaluated for conceptual design: Ottawa River Spar, Spar, Can/Cone, Light/Sound and Bell.Whistle.

The general limitation of the manufacturing processes can be characterized by two main concepts: one consisting of sectional components incorporating processes 1, 2, 3, 4 and 7; and one consisting of unit construction incorporating processes 5, 6, 8, 9 and 11 - as summarized in Table 5-1.

7.1 Resin Selection

The function of a resin in a fibre reinforced composite is to facilitate the transfer of loads from fibre to fibre and protect the fibres from the environment. The choices of resin matrix used in the fabrication of a composite buoy are quite extensive and are somewhat dependent on the application and the function of the resin in the manufacturing process chosen. The best approach to be taken at this stage of development is to state the specific physical properties required. Most composite manufactures will then consult with a resin supplier to determine the specific resin characteristics for a given process. However, with the processes chosen, a general statement can be made with regard to the class of resin to be used. The filament winding process can use thermoplastic or thermoset resins. Production speeds with thermoplastics are significantly slower than those obtained with thermosets. Most filament winding is done with a thermoset polyester or epoxy resins.

Rotational molding and extrusion traditionally use polyethylene or polyurethane resins. To find more specific information on any given resin, consult a reference book such as the "Engineering Plastics".[13]

7.2 Fibre Selection

The choice of fibre for a first interaction of conceptual buoy design should be glass. Glass fibres, although not as strong as other advanced fibres (Table 4-1), still offer comparable strengths to that of steel. At substantially lower prices, Table 4-1, glass fibres offer significant weight reduction. (Density of glass 2.58 g/cm^3 vs steel at 8.03 g/cm^3.) Although a greater weight saving could be obtained through the use of aramid and/or carbon fibres, the increased cost would be significant.

7.3 Process Selection

In addressing each buoy design, the assumption was made that the present basic physical configuration from a functional perspective is adequate. By replacing the steel, the corrosion problem has been eliminated and the weight of the buoy substantially reduced. The problem now is how does one use the technologies available with their own inherent limitations to produce each buoy, and what are the net effects?

The conceptual designs present general configuration for manufacture and assembly. The tailorability of composites makes the matrix of possible designs infinite.

Conceptual designs for the five buoys selected are illustrated on the following pages.

7.4 Ottawa River Spar

The processes that would be deemed favorable for manufacturing the Ottawa River Spar are rotational molding, filament winding and extrusion. The basic configuration for a filament wound or rotational molded buoy would be as illustrated in Figure 7-1. Both processes allow for inclusion of metallic components such as lifting lugs and mooring eyes. Buoy colouring could be added to the resin or done in a post manufacturing process (i.e. painting). The core material would be a closed cell foam.

In the case of filament winding, this foam would serve as the winding mandrel as well as adding additional buoyancy in the case of damage to the outer surface. A buoy fabricated by rotational molding would have the closed cell foam injected in a post manufacturing process. Rotational molding would only allow short fibre reinforcement whereas filament winding allows for continuous fibres.

The extruded Ottawa River Spar would be limited to a cylindrical configuration as shown in Figure 7-1, and like the rotational molded buoy, would only allow short fibre reinforcement. Tooling cost should be lowest for filament wound buoy and highest for the rotational molded buoy. The extruded buoy would require no special tooling (i.e. a suitable profile may already be available).

7.5 Can/Cone

The can/cone buoy lends itself most favorably to fabrication by filament winding, rotational molding and hand/spray lay-up. The basic manufacture would be the same as that of the Ottawa River Spar; however, its configuration is not compatible with extrusion, as shown in Figure 7-2. The can/cone buoy would be manufactured with a fibre reinforced laminated shell enclosing a closed cell foam. The inclusion of metallic inserts allows for easy attachment of mooring and lifting eyes. The fibre reinforcement may be short or continuous depending on the manufacturing process.

7.6 Ice Spar

The ice spar, due to its size and configuration, allows only two processes to be considered for its manufacture: filament winding and extrusion. The extruded ice spar would be configured as the extruded Ottawa River Spar only on a larger scale. A filament wound ice spar could be fabricated as illustrated in Figure 7-3. The ice spar could be manufactured using a closed cell foam in conjunction with a casting salt to form a mandrel to wind around. The salt would be washed out after the laminate had cured allowing cavities for such things as concrete ballast and battery pockets. The design would incorporate metallic inserts wound in place as per the Ottawa River Spar. This would allow for easy attachment of lifting lugs and mooring eyes while protecting the metal from corrosion.

7.7 Light/Sound

A light/sound buoy hull would have only one suitable fabrication method, filament winding. Like the ice spar, a closed cell foam with casting salts would act as the mandrel to wind and allow cavities for battery pockets, etc. as shown in Figure 7-4. All lifting lugs and mooring eyes would be metallic inserts wound in place. These inserts would allow for easy repair and replacement of high wear components such as the mooring bridle attachment points.

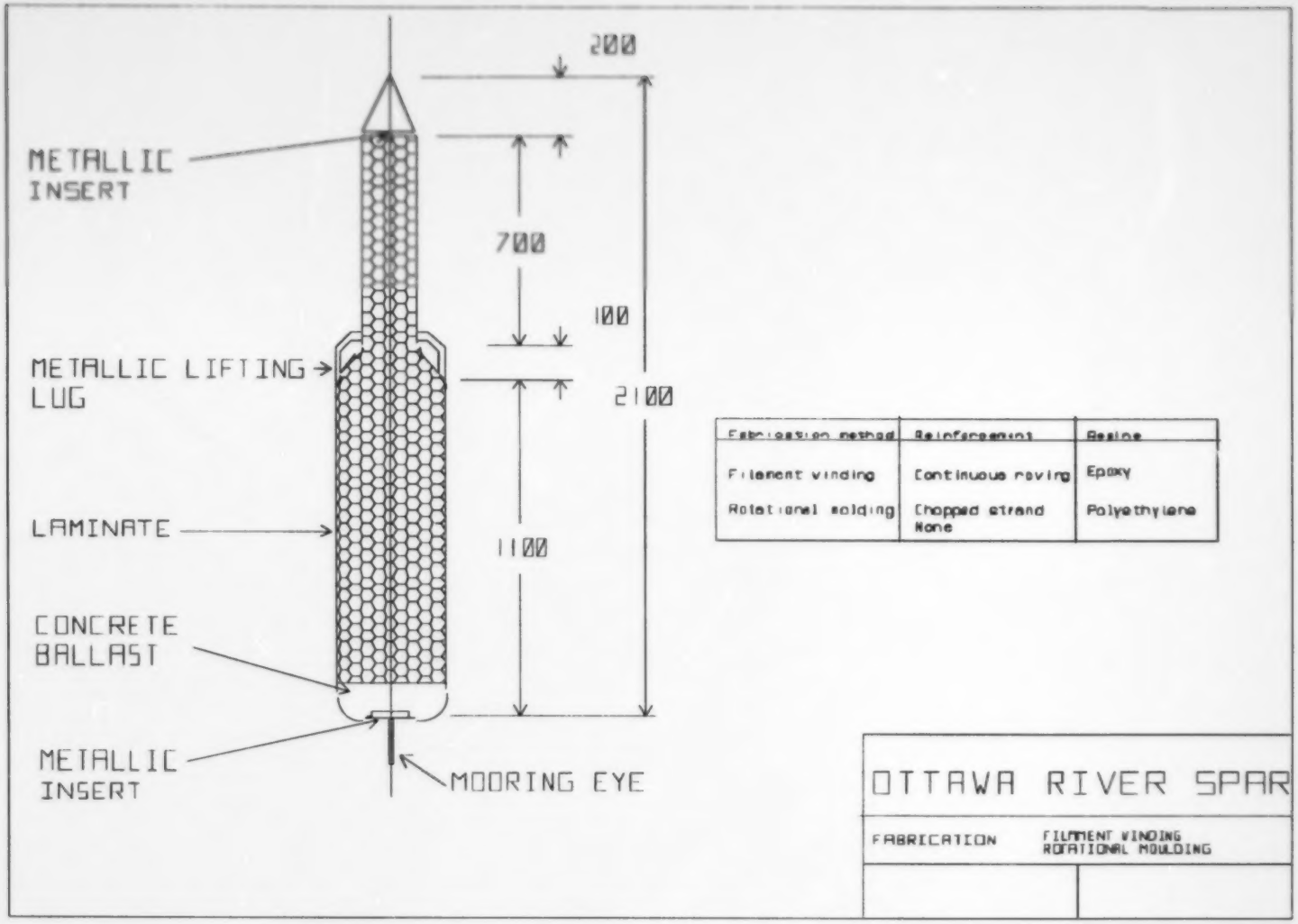


Figure 7-1: Ottawa River Spar

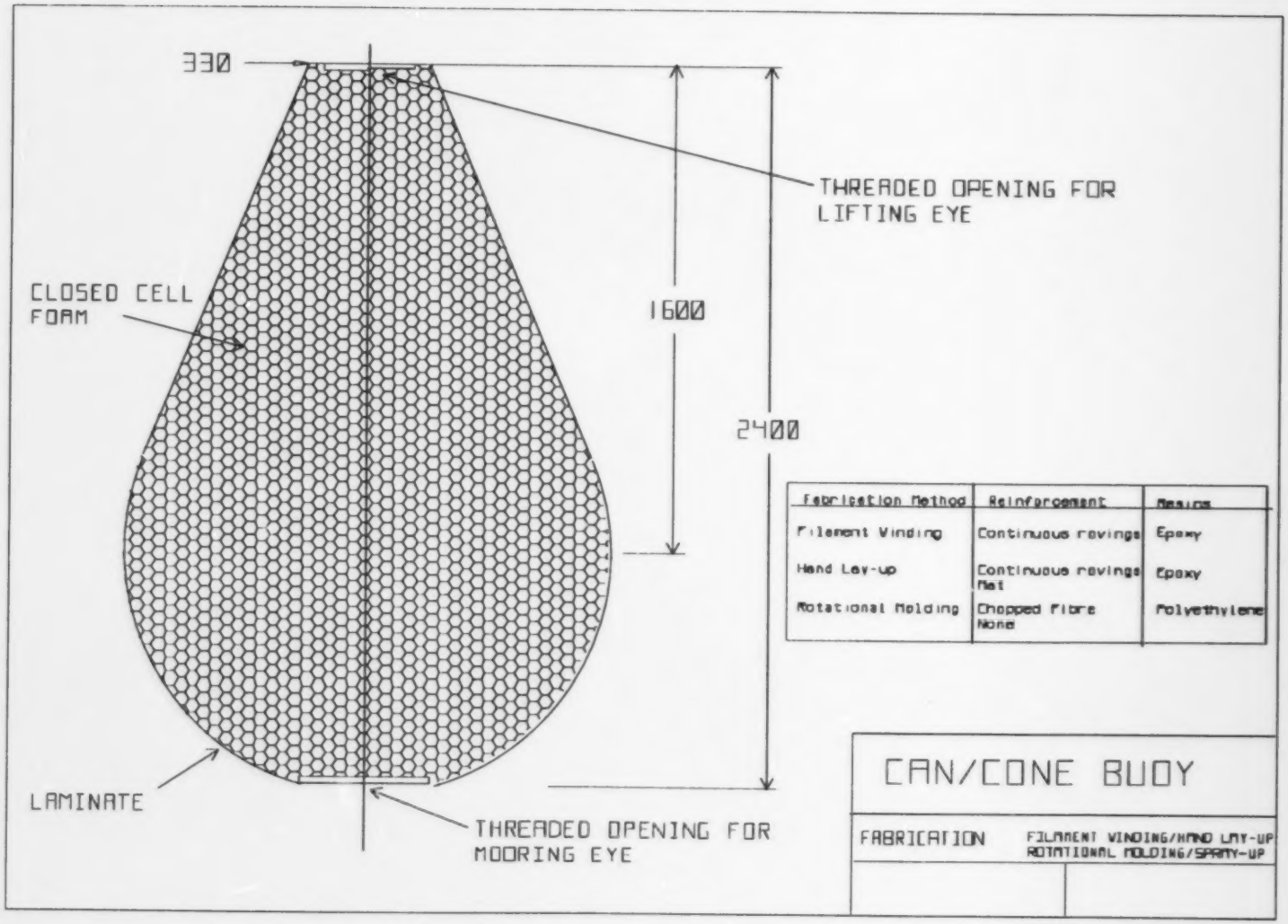


Figure 7-2: Cone Buoy

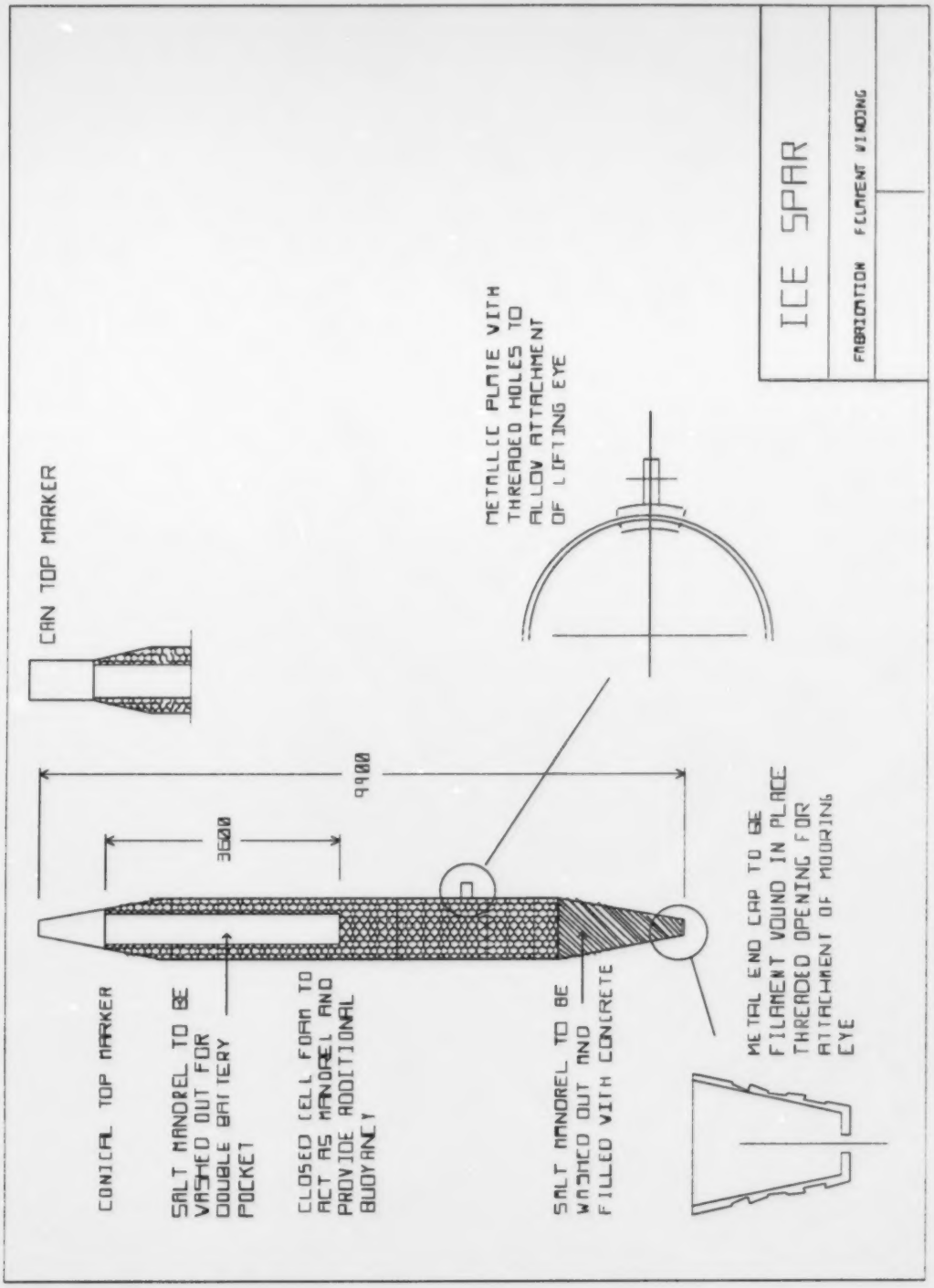


Figure 7-3: Ice Spar Buoy

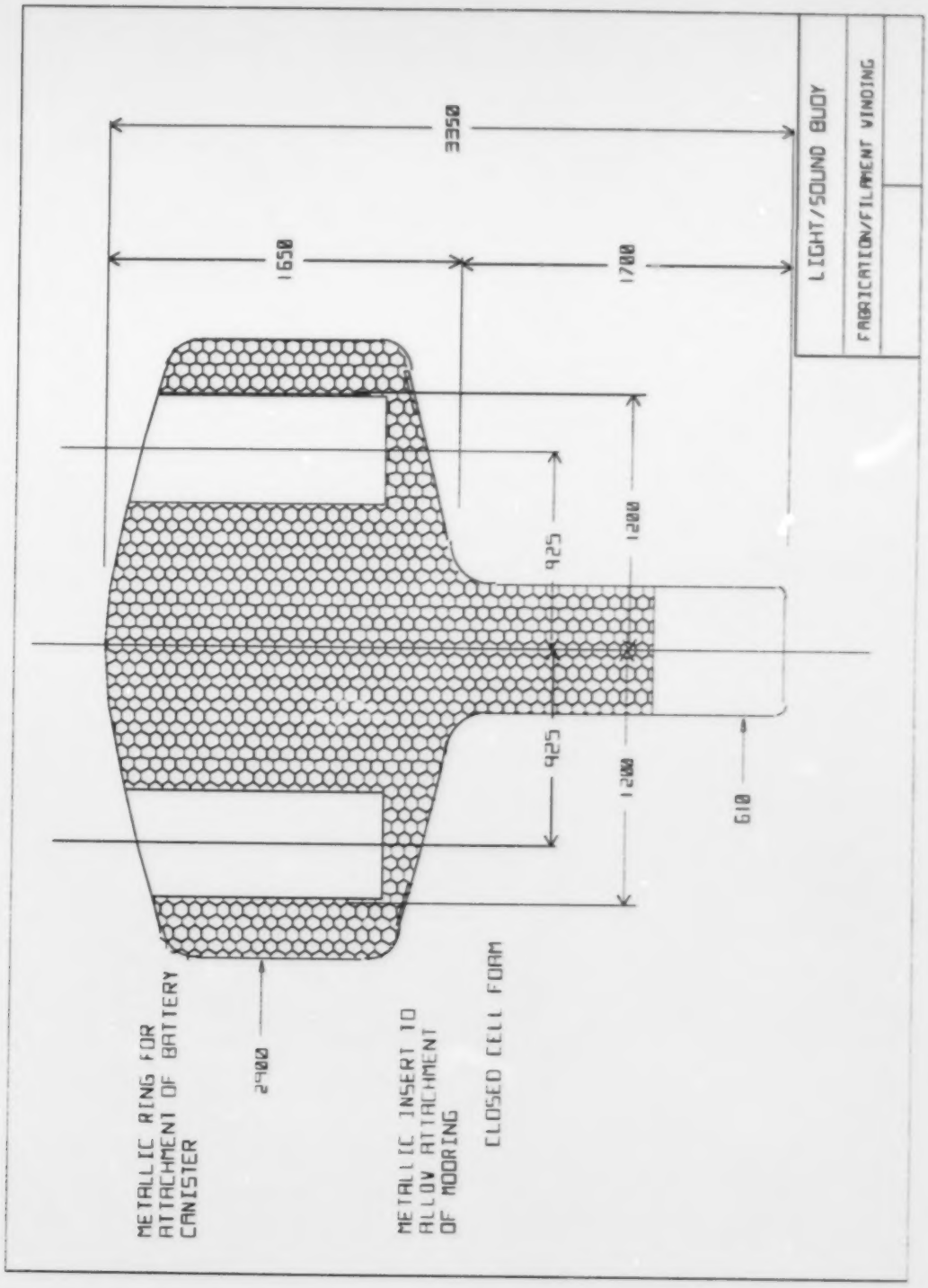


Figure 7-4: Sound Buoy

8. CONCLUSION

In conclusion, the investigation into new technologies available has demonstrated that a navigational buoy of composite construction would be a viable solution to reducing the operational costs of maintaining floating aids for the Canadian Coast Guard. The investigation into technologies has revealed that there are several processes available to produce a composite buoy of advanced materials (see Table 8-1). The processes that appear to be viable solutions are listed in table 8-1. The processes chosen, filament winding, rotational molding, extrusion, and hand/spray lay-up have ranked preferences with each type of buoy. The ranked preference is shown as a bracketed number. Processes chosen with an "X" are plausible choices but are not viable due to intrinsic limitations of the process. The materials cost associated with each process would be relatively consistent (see Table 8-1). The resin matrix and reinforcement fibre is in essence only limited by the fabrication process of choice. A list of readily available matrix/reinforcements vs buoy design is listed in Table 8-2. The initial tooling cost varies with each process, with hand lay-up or filament winding being the least expensive initially, but as volumes increase the other processes become more competitive.The prediction of cost at this stage is very rudimentary and is strictly based on material cost per kilogram times the estimated mass multiplied by a factor of two to allow for 100% mark-up.

Process*	Cross flow Spar	Spar	Can/Cone	Light	Bell/Whistle
Injection molding	X				
Compresion molding	X	X	X	X	X
Transfer molding					
RIM/RTM	X	X	X	X	X
Blow molding	X		X		
Rotational molding	X(1)	X	X(1)	X	X
Thermoforming	X	X	X	X	X
Filament winding	X(2)	X(1)	X(2)	X(1)	X(1)
Hand lay-up/Spray-up	X	X(3)	X(3)	X	X
Pultrusion				superstructure	superstructure
Extrusion	X(3)	X(2)			
Weight (kg)**					
Composite	(16) 39	(311) 1622	(160) 330		(425) 1705
Steel	69	3804	465		4428
Cost (100% Markup) ($)					
E-glass Epoxy	350	6220	3200		8500
Steel	284	1550	2500		16900
Maintenance ($)/Yr (sandblasting, painting, materials, and labour)					
Composite	10	40	50		240
Steel	100	255	244		1145
Life Expectancy (years)					
Composite	20-30	20-30	20-30		20-30
Steel	3	10-15	10-15		30-40

* Bracketed number indicates order of preference
** Bracketed number indicates the weight without ballast

Table 8-1: Comparison of Costs with Comparable Steel Buoy

Maintenance costs should be consistent with each process and appreciably lower than steel (see Table 8-1). The maintenance costs for the composite buoy, as compared to a steel buoy, are based on directs cost to CCG for such items as sand blasting, painting, material repair and labour. The assumption was made that the only cost associated with the composite buoy from a general maintenance perspective would be that of labour (general handling, inspection and washing) which is similar to a steel buoy. The life expectancy of all buoys could be brought in line with that of the existing 2.9 m buoys (as shown in Table 8-1). The life expectancy based on observation of the plastic ice spars in P.E.I. is assumed to be 20-30 years. The lack of any visible signs of deterioration other than a slight fading in original colour of the plastic buoy in P.E.I. suggests this is a reasonable assumption. The most promising conceptual design would be that of a lighted ice spar of filament wound construction. This buoy could be used year round. Preliminary design calculations show a possible 57% weight savings, an approximate 600% maintenance cost savings and a doubling of life expectancy. The ice spar could be subjected to the most severe operating conditions.

Table 8-2: Matrix Reinforcements vs Buoy

MATRIX REINFORCEMENT vs BUOY					
MATRICES	**Ottawa River Spar**	**Spar**	**Can/Cone**	**Light**	**Bell Whistle**
Thermoplastics					
– All					
– Polyester PET	*****	*****	*****	*****	*****
Thermosets					
– Polyester	*****	*****	*****	*****	*****
– Epoxy	*****	*****	*****	*****	*****
– Phenolic	*****	*****	*****	*****	*****
– Polyurethane	*****	*****	*****		
– SMC/BMC					
Reinforcements					
– Continuous Rovings	*****	*****	*****	*****	*****
– Woven Rovings					
– Mat		*****	*****		
– Chopped Strands	*****	*****	*****		
– Milled Fibres					

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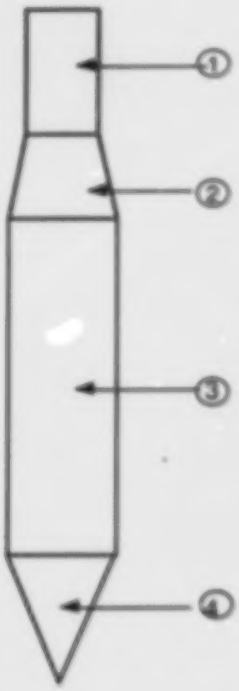
APPENDIX A

ICE SPAR BUOY STABILITY ANALYSIS

Weight Estimate

Item No.	Item	Vol. mm3	Mass kg	VCG (A.B.) mm	Vmom. kg mm
1	Cyl No. 1 (1900)	5.527×10^7	77.87	8550	665789
2	Cyl No. 2 (1900)	6.350×10^7	89.47	6610	591397
3	Cyl No. 3 (3800)	14.35×10^7	202.15	3800	768170
4	Concrete Ballast	55.68×10^7	1336.34	1308	1747933
	Total		1705.83	2212	3773289

Light Draft = 3306 mm A.B.
Light Ship = 1.706 kg
(without marine growth)



Spar Buoy (New Design)

All vertical dimensions are given as heights above baseline (A.B.) in meters.

Vertical Center of Gravity (VCG)	=	2.212 m.....A.B.
Displacement	=	1.706 tonnes
Design Water Line	=	3.306 m.....A.B.
Underwater Center of Lateral Area	=	1.986 m.....A.B.
Underwater Projected Lateral Area	=	2.669 m^2
Height of Deck Edge	=	9.50 m .....A.B.
Height of Cable Anchor Point	=	0.0 m.....A.B.
Depth of Water	=	15.00 m
Scope of Anchor Cable	=	5:1
Length of Anchor Cable	=	75.00 m
Current Speed	=	4.00 knots
Wind Speed	=	35.00 knots

Mooring Loads

The mooring forces acting on the buoy are illustrated in Figure 5.1 of the manual.

Horizontal Component (T_{BH})

$T_{BH} = \frac{1}{2} CD \cdot P \cdot Ap \cdot (Vc)^2$ (Sect. 5.2.1.)

CD = 0.5 for cylinders

p = 1025 Kg/m^3

Ap = 2.669 m^2

Vc = 4 kt = 2.057 m/sec

T_{BH} = 2894 N

Style of the Moored Line (θ_B):

$$\text{Tan } \theta_B = \frac{P \cdot S}{2 \cdot T_{BH}} + \frac{P \cdot d}{2 \cdot T_{BH}} \left[1 + \frac{4\, T_{bm}^2}{P^2 (S^2 + d^2)} \right]^{1/2}$$

(Eq. 2 in Sect. 5.2.1.)

T_{BH} = 2894 N

P = 160.8 N/m in water for 1 - 1/8" chain

S = 75 m

d = 15 m

Tan θ_B = 2.5478

θ_B = 68.6 Deg.

Tension in Mooring Line (TB):

$T_B = T_{BH}/\text{Cos}\theta_B$ (Eq. 3, Sect. 5.2.1.)

T_B = 7620 N

Vertical Component (T_{BV}):

$T_{BV} = T_B/\text{Sin}\theta_B$ (Eq. 4, Sect. 5.2.1.)

T_{BV} = 7373 N

Initial Sinkage:

$d = T_{BV}/100{,}000\ g\ TPC$ (Eq. 5, Sect. 5.2.1.)

TPC = 0.00807 tonnes/cm

$g = 9.807\ m/sec^2$

d = 0.9316 m

The revised draft due to initial sinkage is 3.306 + 0.9316 = 4.237 m

An additional sinkage of 0.52 m can be expected. The additional drag force will be calculated for a total sinkage of 0.9316 + 0.52 = 1.4516 m

Additional Horizontal Component

$T_{BH} = \frac{1}{2} CD \cdot P \cdot Ap \cdot (Vc)^2 = 1596\ N$

Cd = 0.5

$P = 1025\ Kg/m^3$

Ap = 1.472 m2 (buoy diam. x (inc. draft + 0.520 m)

Vc = 4 kt = 2.057 m/sec

Additional Tension in Mooring Line

$T_B = T_{BH}/Cos\theta_B = 4368$

Assuming same angle θ_B as previous calculation.

Additional Vertical Component

$T_{BV} = T_B/Sin\theta_B = 4066\ N$

Additional Sinkage:

$d = T_{BV}/100{,}000 \cdot TPC \cdot g$

TPC = 0.00807 tonnes/cm

d = 0.514 m

Calculated additional sinkage is 0.514 m versus assumed 0.52 m. The difference is less than 1 cm.

Total Sinkage	=	1.446 m
Total Horizontal Component	=	4490 N
Total Vertical Component	=	11439 N
Total Line Tension	=	11988 N

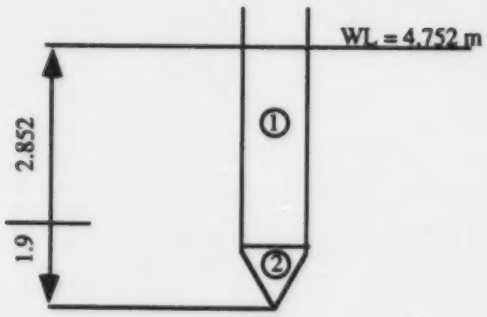
UPSETTING MOMENT INDUCED BY THE MOORING SYSTEM:

Center of the lateral area below the waterline:

	A(M^2)	VCG (M)
Under 3.306 m W.L.	2.669	1.986
Total Sinkage	1.466	4.099
	4.135	2.735

Upsetting Moment = 4490 x 2.735 = 12280 N m
= 1.252 tonnes • m

Marine Growth



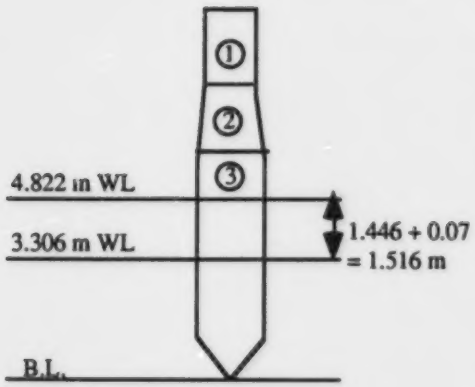
	Project Underwater Lateral Area (m^2)	V.C.G. of the Projected Area m (A/B)
1	2.963	3.361
2	1.172	1.154
	4.135	2.734

Weight of the marine growth = 0.02 x 2.872 = 0.057 tonnes

V.C.G. of the marine growth = 2.734 m (A/B)

Additional sinkage = 0.07 m

Wind Loads



Projected area above 4.822 m WL and its center of gravity

	A(M^2)	VCG (M)
1.	2.669	1.986
2.	1.708	1.695
3.	1.466	4.099
	4.088	2.163

Projected area = 4.088 m^2
VCG (A/B) = 2.163 + 4.822 = 6.985 m

Total Wind Force

$F_D = \frac{1}{2} \cdot a \cdot C_D \cdot A \cdot (Vm)^2$

C_D = 0.5 for cylinder

a = 1.0 kg/m^3

A = 4.088 m^2

Vm = 35 kt = 18.004 m/sec (Sect. 5.2.3.)

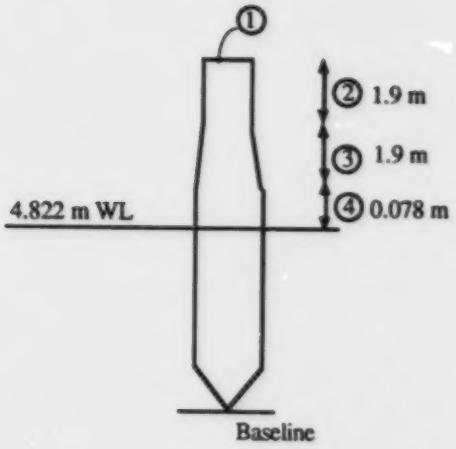
F_D = 331.27 N

Using the center of the lateral resistance 2.735 m the lever for wind heeling moment can be calculated as 6.985 - 2.735 = 4.25 m

Hence:

The Wind Heeling Moment = 331.27 x 4.25
= 1408 N m
= 0.144 tonnes m

Ice Accretion



Item	Area m^2	Standard kg/m^2	Ice Wgt kg/m^2	VCG m A/B
1	0.482	50	24.25	9.500
2	4.677	15	70.15	8.550
3	5.363	17	91.17	6.610
4	2.796	15	41.94	5.261
		Total	**227.51**	**7.268**

Total Accumulated Ice = 0.228 tonnes
Vertical Center of Gravity = 7.268 m A/B
Additional Sinkage = 0.283 m

Stability and Buoyancy Assessment

Total weight and center of gravity of the spar buoy:

	Wgt (t)	VCG (m)
Intact Buoy	1.706	2.212
Vertical Mooring Loads	1.166	0.000
Marine Growth	0.057	2.734
Displ. w/o Ice	2.929	1.342

For Icing Condition

Displ. w/o Ice	2.929	1.342
Ice	0.228	7.268
Displ. with Ice	3.157	1.77

Hydrostatics

Draft m (A/B)	Displ. (t)	VCB m (A/B)	KM m (A/B)
4.822	2.929	2.96	2.978
5.105	3.157	3.105	3.122

Righting Arms

Without Ice (VCG = 1.342)

Angle	15°	30°	45°	60°	75°	90°
KN (m)	0.75	1.41	2.05	2.52	2.92	4.82
GZ (m)	0.40	0.74	1.10	1.36	1.62	3.48

With Ice (VCG = 1.77 m)

Angle	15°	30°	45°	60°	75°	90°
KN (m)	0.77	1.47	2.15	2.65	3.05	4.84
GZ (m)	0.31	0.59	0.90	1.12	1.34	3.07

Condition Without Ice

Heeling Arm Due to Mooring Load

$$MHA = \frac{\text{Mooring Moment}}{\text{Displ.}} = \frac{1.252}{2.929} = 0.427 \text{ m}$$

Heeling Arm Due to Wind Loads

$$WHA = \frac{\text{Wind Moment} \times \cos^2\theta}{\text{Displ.}} = \frac{0.144 \cdot \cos^2\theta}{2.929}$$

θ	WHA (m)
0	0.049
15	0.046
30	0.037
45	0.025
60	0.012
75	0.003
90	0.000

Reserve Buoyance (Freeboard)

Condition Without Ice

$$d = \frac{\text{Wind Moment + Mooring Moment}}{\text{Displacement}}$$

$$d = \frac{0.166 + 1.252}{2.929} = 0.477$$

$$\text{Cos}\,\theta = \frac{GM}{d} = \frac{1.636}{0.477} \rightarrow \theta = 16.25^{\circ}$$

Freeboard (without heel) = 4.678 m

Freeboard (with heel) = 4.678 x Cos 16.25°
= 4.491 m

Condition With Ice

Heeling arm due to mooring:

$$MHA = \frac{1.252}{3.175} = 0.394$$

Heeling arm due to wind:

$$WHA = \frac{\text{Moment x Cos}^2\theta}{\text{Displacement}} = \frac{0.144 \text{ x Cos}^2\theta}{3.175}$$

θ	WHA (m)
0	0.046
15	0.043
30	0.034
45	0.022
60	0.011
75	0.003
90	0.000

Reserve Buoyance (Freeboard)

Condition With Ice

$$d = \frac{\text{Wind Moment} + \text{Mooring Moment}}{\text{Displacement}}$$

$$d = \frac{0.144 + 1.252}{3.157} = 0.442$$

$$\text{Cos } \theta = \frac{GM}{d} = \frac{1.352}{0.442} \quad \rightarrow \quad \theta = 18.10^{\circ}$$

Freeboard (without heel) = 4.395 m

Freeboard (with heel) = 4.395 x Cos 18.10°
= 4.177 m

APPENDIX B

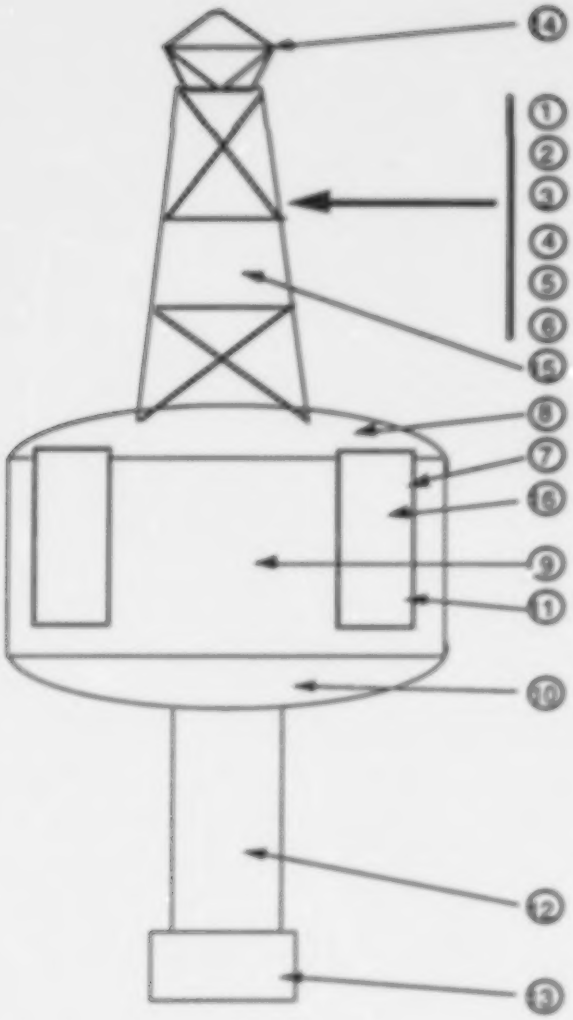
LIGHT BUOY STABILITY ANALYSIS

Weight Estimate

Item No.	Description	Vol. mm^3	Mass kg	V.C.G. m	V.mt. kg m
1	4 L65 x 65 x 8 (L = 1085)	0.424×10^7	5.968	6.33	37.78
2	4 L65 x 65 x 8 (L = 1085)	0.424×10^7	5.968	5.43	32.41
3	4 L125 x 75 x 8 (L = 1085)	0.667×10^7	9.393	4.88	45.84
4	2 L45 x 45 x 6 (L = 1650)	0.166×10^7	2.344	4.115	9.65
5	4 L45 x 45 x 6 (L = 1300)	0.262×10^7	3.692	4.498	16.61
6	4 L90 90 x 8 (L = 2980)	1.640×10^7	23.11	4.84	111.85
7	2 Battery Holders w/top & bot.	5.397×10^7	76.056	2.79	212.20
8	Upper Sphere	5.912×10^7	83.30	3.15	262.39
9	Cylinder	7.021×10^7	98.93	2.52	249.30
10	Lower Sphere	5.912×10^7	83.30	1.89	157.44
11	6 Brackets 300 x 300 x 8	0.216×10^7	3.04	1.60	4.86
12	610 mm Tube (L=2300)	4.333×10^7	61.05	1.395	85.16
13	Counter Weight		720.00	0.123	88.56
14	Reflectors		15.00	5.73	85.95
15	Brass Bell		300.00	4.78	1434.00
16	Battery Pack		258.00	2.79	719.82
	Total		1749.15	2.032	3553.82

Displacement = 1.749 Tonnes

Vertical Center Gravity = 2.032 m (A/B)


14
1
2
3
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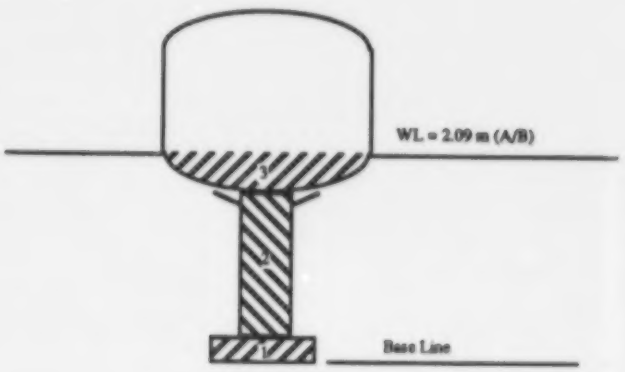
Projected Area Under the Waterline:



ITEM	AREA m2	VCG m(A/B)
1	0.24	0.123
2	0.888	1.095
3	0.706	1.928
Total	1.834	1.288

Projected Lateral Area (Under Water) = 2.354 m2

V.C.A. and the Projected Area = 1.395 m

Principal Particulars:

Displacement	=	1.749 Tonnes
Vertical Center of Gravity	=	2.032 m (A/B)
Design Water Line	=	2.09 m (A/B)
Underwater Projected Lateral Area	=	1.834 m^2
Underwater Center of Lateral Area	=	1.288 m (A/B)
Height of Deck Edge	=	2.950 m (A/B)
Height of Cable Anchor Point	=	1.900 m (A/B)
Depth of Water	=	40.00 m
Scope of Anchor Cable	=	4.1
Length of Anchor Cable	=	160.00 m
Current Speed	=	6 knots
Wind Speed	=	60 knots

Mooring Loads

The mooring forces acting on the buoy are as shown in Figure 5.1 in buoy design manual.

Horizontal Component (T_{BH})

$T_{BH} = 1/2\, C_D \cdot P \cdot A_p \cdot (V_c)^2$ (Sect. 5.21)

$C_D = 0.5$ for Cylinders

$p = 1025\ kg/m^3$

$A_p = 9.834\ m^2$

$V_c = 6\ kt = 3.086\ m/sec$

$T_{BH} = 4476\ N$

Angle of the Mooring Line (θ_B):

$$\text{Tan}\,\theta = \frac{P \cdot S}{2 \cdot T_{BH}} + \frac{P \cdot d}{2 \cdot T_{BH}}\,1 + \left[\frac{4 \cdot T_{BH}^2}{p^2(S^2 + d^2)}\right] 1/2$$

(Eg. 2 in Sect. 5.2.1.)

T_{BH} = 4476

P = 100 N/m

s = 160 m

d = 40 m

Tan θ_B = 2.3

θ_B = 66.57 Deg

Tension in Mooring Line (T_B):

T_B = T_{BH}/Cos θ_B (Eg. 3, Sect. 5.2.1)

T_B = 11239 N

Vertical Component (T_{BV}):

T_{BV} = T_B Sin θ_B (Eg. 4, Sect. 5.2.1)

T_{BV} = 10310 N

Initial Sinkage:

$d = T_{BV}/100000 \cdot g \cdot TPC$ (Eq. 5, Sect. 5.2.1)

$TPC = 0.054$ Tonnes/Cm

$g = 9.807$ m/sec^2

$d = 0.195$ m

The revised draft due to initial sinkage is $2.09 + 0.195 = 2.285$ m

An additional sinkage of 0.08 m can be expected. The additional drag force will be calculated for a total sinkage of $0.195 + 0.08 = 0.275$ m.

Additional Horizontal Component:

$T_{BH} = 1/2\ C_D \cdot p \cdot A_p \cdot (V_c)^2 = 1745$ N

$E_D = 0.5$

$p = 1025$ kg/m^3

$A_p = (0.175 + 0.08) \times 2.6 = 0.715$ m^2

$V_c = 3.086$ m/sec

Additional Tension in the Mooring Line:

$T_B = T_{BH}/\text{Cos}\ \theta_B = 4382$ N

Assuming same argyle $\theta_B = 66.579$

Additional Vertical Component:

$T_{BV} = T_B \cdot \text{Sin}\theta_B = 4019$ N

Additional Sinkage:

$d = T_{BV}/100000 \cdot g \cdot TPC$

TPC = 0.054 Tonnes/cm

d = 0.076 m

Calculated additional sinkage is 0.076 versus assumed 0.08 m. The difference is less then 1 cm.

Total Sinkage	=	0.271 m
Total Horizontal (Drag) Component	=	6221 N
Total Vertical (Drag) Component	=	14329 N
Total Line Tension	=	15621 N

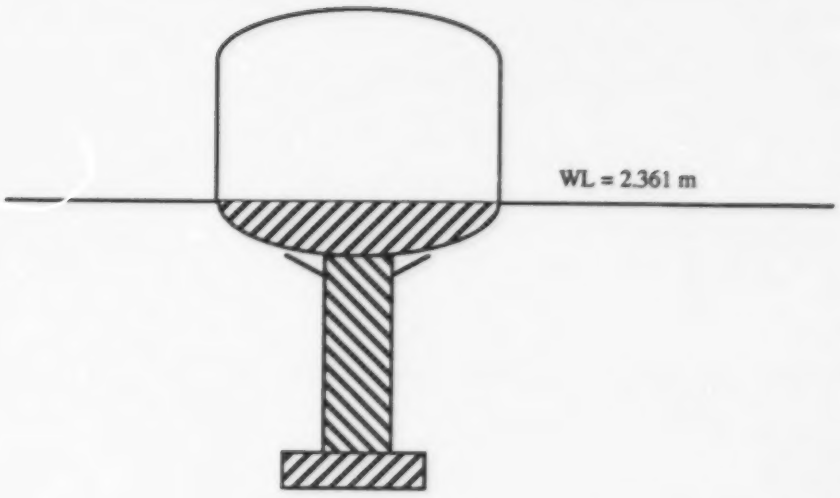
Center of the lateral area below the new waterline:

	A(m2)	VCG(m)
Under 2.09 m W.L.	1.834	1.288
Total Sinkage	0.705	2.226
Total	2.539	1.548

Anchor cable pivot point is located at 1.900 m (A/B)
The lever for the upsetting moment = 1.9 - 1.548 = 0.342 m

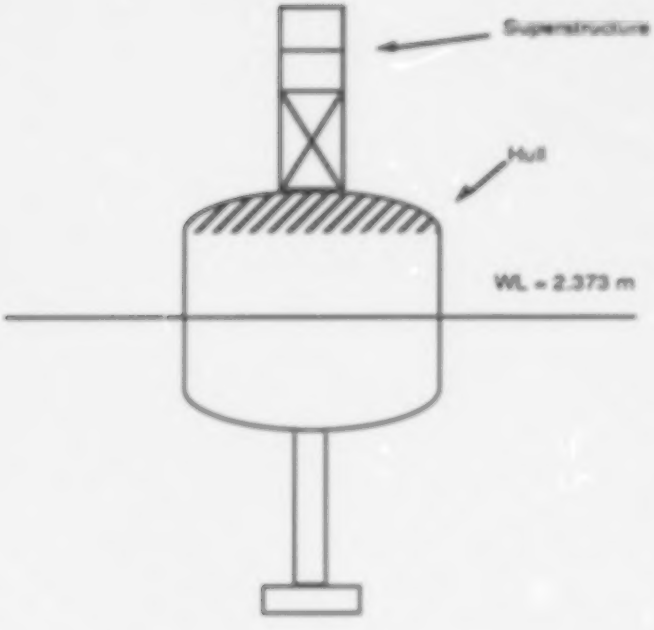
Upsetting Moment = 6221 x 0.352 = 2189.79 Nm
= 0.223 Tonnes M

MARINE GROWTH



Weight of the Marine Growth	=	0.02 x 3.21 = 0.064 Tonnes
V.C.G. of the Marine Growth	=	1.548 m (A/B)
Additional Sinkage due to the Marine Growth	=	0.012 m

WIND LOADS



Projected Area and its Centre:

	A(m2)	VCG(m) A/B
Superstructure	1.730	3.860
Hull	2.280	2.560
Total	4.01	3.12

Wind Force:

$F_D = 1/2 \cdot a \cdot C_D \cdot A \cdot (V_w)^2$

C_D = 0.5 for Hull
= 1.5 for Superstructure

a = 1.0 kg/m^3

A = 3.215 for Superstructure
= 2.297 for Hull

V_w = 60 knots = 30.864 m/sec.

For Hull:

$F_D = 0.5 \times 1.0 \times 0.5 \times 2.28 \times (30.864)^2$
F_D = 542.97 N

For Superstructure:

$F_D = 0.5 \times 1.0 \times 1.5 \times 1.73 \times (30.864)^2$

F_D = 411.99 N

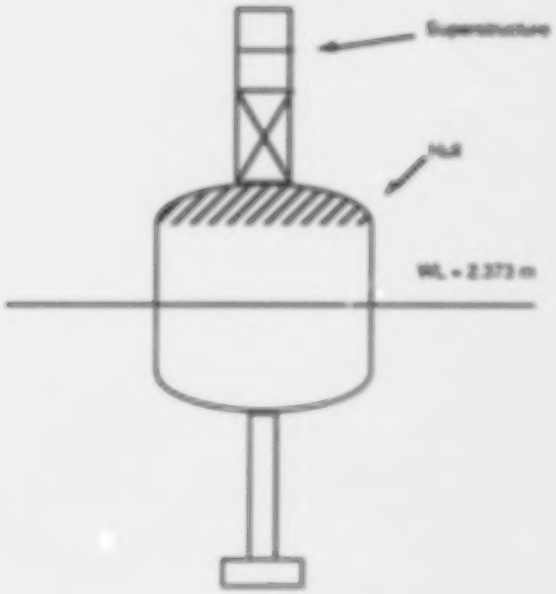
Total Force:

F_D = 955 N @ 3.12 m/ A/B

Using the center of the lateral resistance 1.548 m the lever for wind heeling movement can be calculated as 3.120 - 1.548 = 1.572 m.

The wind heeling movement = 955 x 1.572
= 1501.26 Nm
= 0.153 Tonnes m

ICE ACCRETION



ITEM	ASS(kg)	VCG(m) A/B
Battery Holder	154	3.33
Upper Sphere	500	3.15
Hull Side	118	2.66
Superstructure	870	4.88
Total	1642	4.048

Weight of Ice = 1.642 Tonnes

Vertical Center of Gravity = 4.048 m (A/B)

Additional Sinkage = 0.297 m

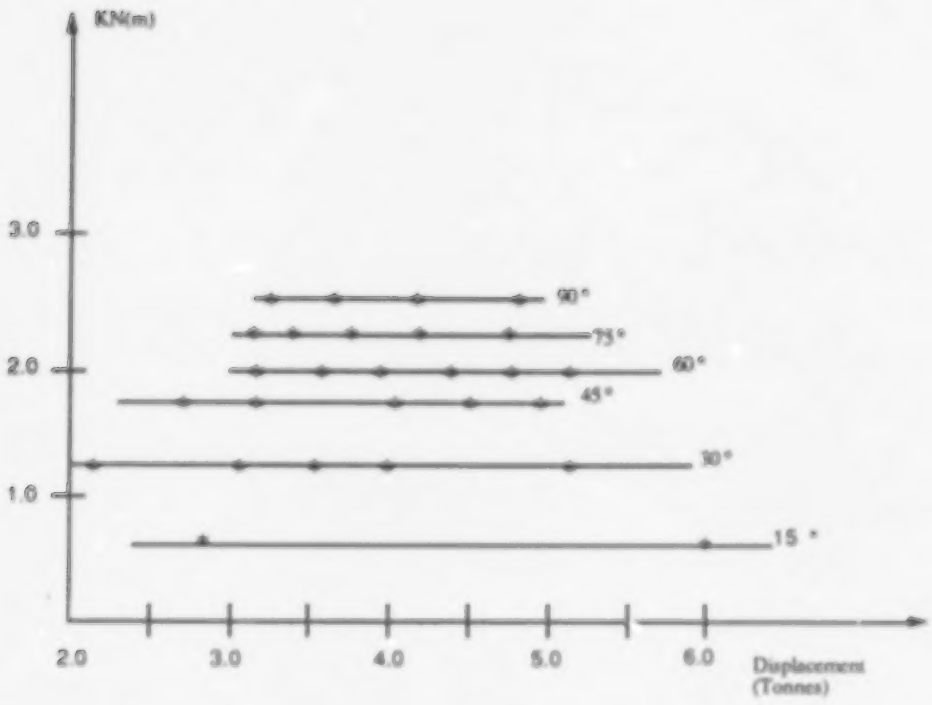
STABILITY AND BUOYANCY ASSESSMENT

Total Weight and Center of Gravity of the Bell Buoy:

	Wgt.(T)	VCG (M)
Intact Buoy	1.747	2.032
Vertical Mooring Loads	1.461	1.900
Marine Growth	0.064	1.548
Total Without Ice	3.274	1.964

For Icing Condition:

	Wgt.	VCG
Displ without Ice	3.274	1.964
Ice	1.642	4.048
Total	4.916	2.66



Cross Curves of Stability

Hydrostatics

Draft m(A/B)	Displ (T)	VCB m(A/B)	KM m(A/B)
2.373	3.274	1.848	2.547
2.670	4.916	2.070	2.539

Righting:

Without Ice (VCG = 1.964 m)

Angle	15°	30°	45°	60°	75°	90°
KN(m)	0.67	1.28	1.76	2.08	2.24	2.41
GZ(m)	0.16	0.298	0.371	0.379	0.343	0.446

With Ice (VCG = 2.66 m)

Angle	15°	30°	45°	60°	75°	90°
KN(m)	0.66	1.28	1.77	2.11	2.29	2.34
GZ(m)						

Condition Without Ice

Heeling Arm due to Mooring Loads

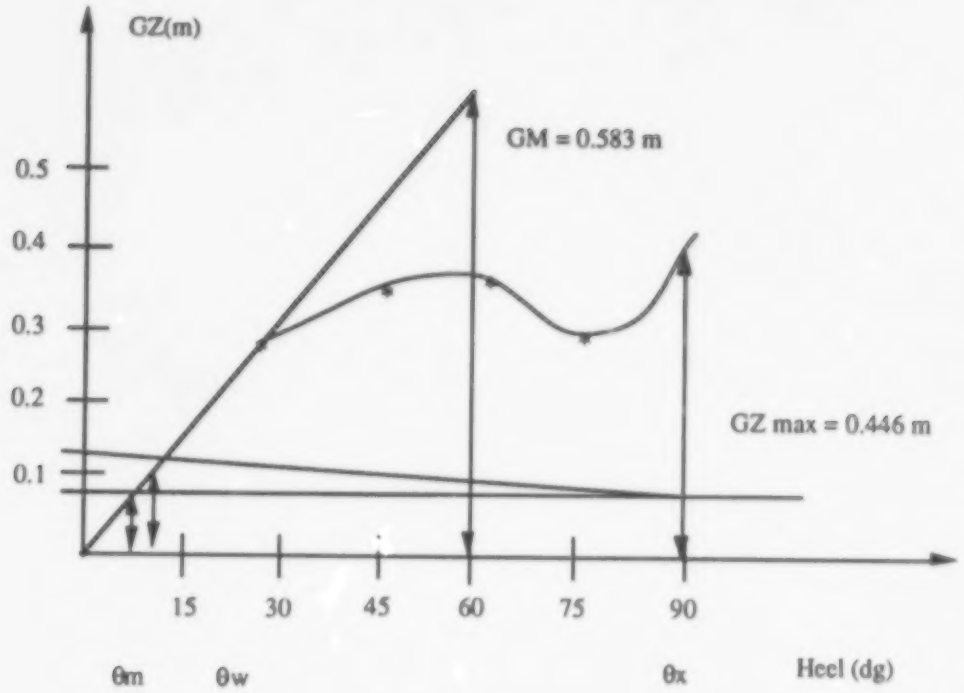
$$MHA = \frac{\text{Mooring Moment}}{\text{Displ}} = \frac{0.223}{3.274} = 0.068 \text{ m}$$

Heeling Arm due to Wind Loads:

$$WHA = \frac{\text{Wind Moment} \times \text{Cos}^2\theta}{\text{Displ}} = \frac{0.153 \times \text{Cos}^2\theta}{3.274}$$

θ (DEG)	WHA (m)
0	0.047
15	0.044
30	0.035
75	0.023
60	0.011
75	0.003
90	0.000

Condition Without Ice:

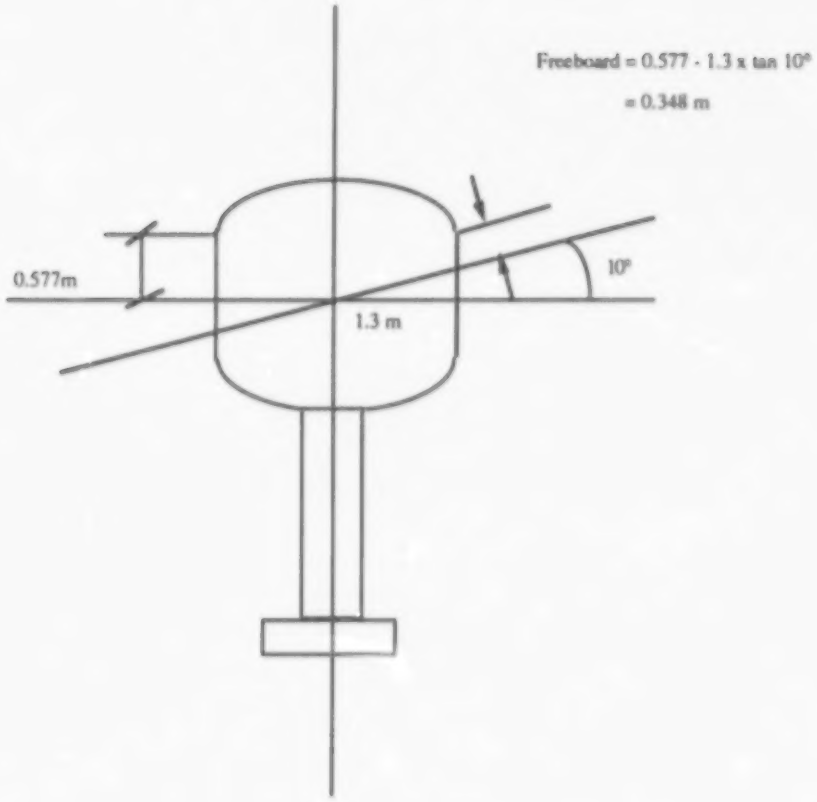


GZ max	=	0.446 m
GM	=	0.583 m
θ_w	=	10 Deg
θ_m	=	6 Deg
GZ_w	=	0.110 m
WHA	=	0.047 m
MHA	=	0.068 m
θ_x	=	90 Deg
θ_R	>	90 Deg

Reserve Buoyancy (Freeboard)

Condition Without Ice:

Angle of Reel (Wind and Current) = 10 Deg.



APPENDIX C

ICE SPAR BUOY DESIGN CALCULATIONS

ICE SPAR DESIGN

Loads

a. Lifting Lugs
b. Hull
c. Superstructure
d. Mooring Lug

Water Line = 4.82 m

F/B = 4.65 m

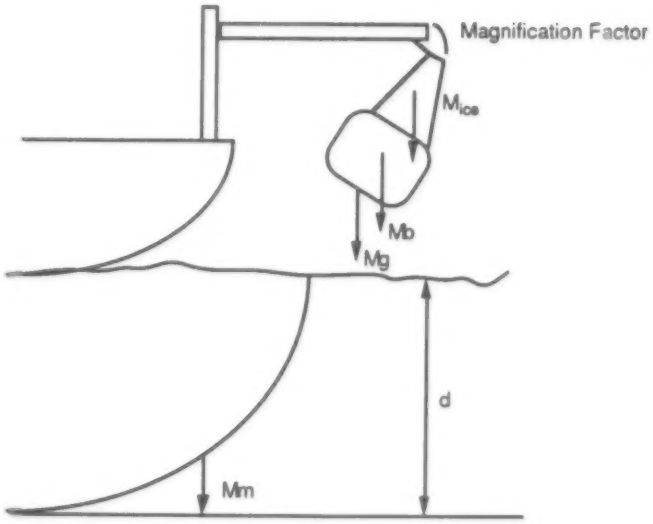
Wave Ht. = 6.0 m

Wave Period = 5 sec.

Wind Vel. = 35 knots = 18 m/s

Current Vel. = 4 knots = 2 m/s

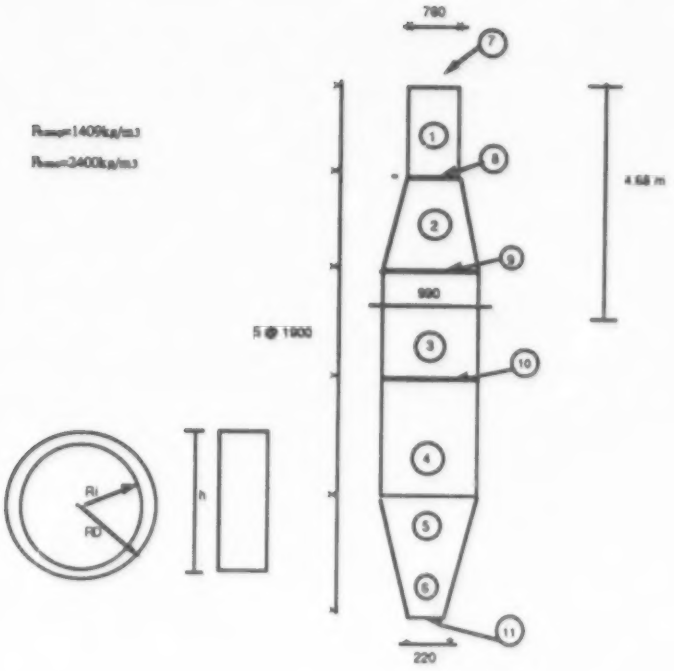
1.1 Determine Load on Lifting Lug



$$M_T = (M_b + M_m + M_f + M_{ice})g$$

where:
M_T = total static load on lifting pt.
M_b = buoy mass
M_m = mooring mass (kg/m • d)
M_f = fouling mass (10-40 kg/m2/year)
M_{ice} = Icing mass (2.6.1)

Buoy Mass



$$V = \pi(Ro^2 - Ri^2)\, h$$

$$V_1 = \pi((0.392)^2 - (0.380)^2)\,(1.90) = \underline{0.0553}\ m^3$$

$$V_3 = \pi((0.507)^2 - (0.495)^2)\,(1.90) = \underline{0.0718}\ m^3$$

Approx. Calc: $A = \pi D_m t$
where Dm is mean dia.

$$V_4 = V_3$$

$$V_2 = \pi\left(\frac{.990 + .760}{2}\right)(0.012)\,(1.90) = 0.0627\ m^3$$

$$V_5 = \pi\left(\frac{0.990 + 0.220}{2}\right)(0.012)\,(1.90) = 0.0433\ m^3$$

$$V_7 = \pi\left(\frac{.760}{2}\right)^2 (0.012) = \underline{0.00544}\ m^3$$

$$V_8 = \pi\left(\frac{0.760 + 0.610}{2}\right)\left(\frac{0.760 - 0.610}{2}\right)(0.010) = \pi(0.685)\,(0.075)\,(0.010) = \underline{0.00161}\ m^3$$

$$V_{9+10} = 2\pi\left(\frac{0.990 + 840}{2}\right)\left(\frac{0.990 - 0.840}{2}\right)(0.010) = \underline{0.00431}\ m^3$$

$$V_{11} = \pi\left(\frac{0.220}{2}\right)^2 (0.010) = \underline{0.00038}\ m^3$$

$$V_{Total\ Comp} = (0.0553) + 2(0.0718) + (0.0627) + (0.0433) + (0.00544) + (0.00161) + (0.00431) + (0.00038) = \underline{0.317}\ m^3$$

$$V_{conc} = \pi\left(\frac{(0.220) + (0.990)}{4}\right)^2 (1.90) = \underline{0.546}\ m^3$$

$$M_{comp} = \left(1409\ {}^{kg}/_{m^3}\right)(0.317\ m^3) = \underline{447}\ kg$$

$$M_{conc} = \left(2400\ {}^{kg}/_{m^3}\right)(0.546\ m^3) = \underline{1310}\ kg$$

$$M_b = 1310 + 447 = 1760\ kg$$

Ice Load

From table 2.7 Ice Buoy: Vert. = 25 kg/m^2
Horiz.. = 150 kg/m^2

Total Vertical Surface Area:

$$1.9\,\pi\left(0.808 + \left(\frac{1.038 + 0.808}{2}\right)\right) + 0.88\,\pi\,(1.038) = 10.33 + 2.87 = 13.2\text{m}^2$$

Ice Load on Vertical Surface:

$= (13.2)\,(25) = \underline{330\text{ kg}}$

Ice Load on Horizontal Surface:

$= \pi(.404)^2\,(150) = 76.9\text{ kg}$

$\therefore\ M_{16} = \text{Total Ice Load} = 330 + 76.9 = \underline{407\text{ kg}}$

Marine Growth

Underwater Surface Area:

$$= \pi(1.9)\left(\left(\frac{1.038 + 0.268}{2}\right) + 1.038\right) + \pi\,(1.038)\,(1.02) = 13.4\ m^2$$

Assume marine growth of 40 $kg/m^2/yr$

$M_f = 13.4\,(40) = \underline{536}\ kg$

Cable Mass

= (mass/metre in water) (depth)

assume: chain = 1 1/8" 1100 lb/100 ft = 16.4 kg/m

water depth = 15 m

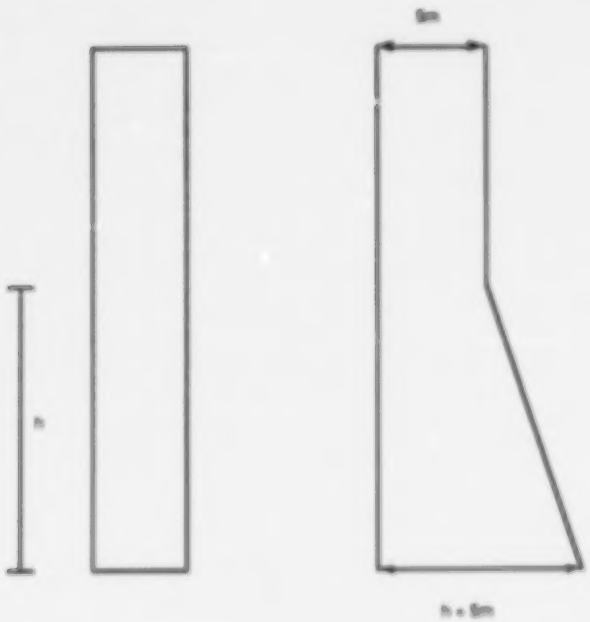
$1\ {}^{lb}/_{ft} = 1.488 \quad 164\ {}^{kg}/_{m}$

$M_m = (15)(16.4) = 246\ kg$

$$\begin{aligned} \text{Total Load } M_T &= [M_b + M_m + M_f + M_{ice}]\, g \\ &= (1760 + 246 + 536 + 407)\, g \\ &= 2949\ (9.81) \\ M_T &= 28.9\ K_N \end{aligned}$$

Hull Loads

$P = \rho g h$ where ρ = 1025 kg/m = salt water (4.2)
g = 9.81 m/s
h = vessel draft in metres



Superstructure Load:

$F = m \cdot w \cdot r$ where m = mass under consideration (4.3)
r = the distance of the mass for the buoys static waterline
w = is the angular acceleration of the buoy caused by the wave action.

$$m = (9.5 - 4.82)(0.99)\pi(0.012)\left(1409\ {}^{kg}/_{m^3}\right) = 246\ kg$$

$$r = \left(\frac{9.5 - 4.82}{2}\right) = 2.34\ m$$

$$w = \frac{\theta}{Tp^2} \qquad (4.3.1)$$

$$Tp = \frac{2k}{\sqrt{GM}} \qquad (4.3.1.1)$$

K = the buoys radius of gyration about an axis through G.
GM = the buoys metacentric height
G = the buoys centre of gravity

$$Tp = \frac{0.7\,D}{\sqrt{GM}} = \frac{0.7\,(0.99)}{\sqrt{1.352}\text{ (for stability calc.)}} = 0.596 \qquad (4.3.1.1\text{ (a)})$$

$$\theta = \frac{\pi H}{L}\left(\frac{T^2}{T^2 - Tp^2}\right)$$

T = wave period = 5 sec. (4.3.1.1(d))
H = wave height = 6.0 m
L = wave length = $\frac{gT^2}{2\pi}$

$$= \frac{\pi(6)}{\frac{(9.81)(5)^2}{2\pi}}\left(\frac{(5)^2}{(5)^2 - (0.596)^2}\right) = \underline{0.49\text{ radians}}$$

$$w = \frac{0.49}{(0.596)^2} = 1.38\ \text{rad/s}^2$$

$$F = (246)(1.380)(2.34) = 794\ \text{N}$$

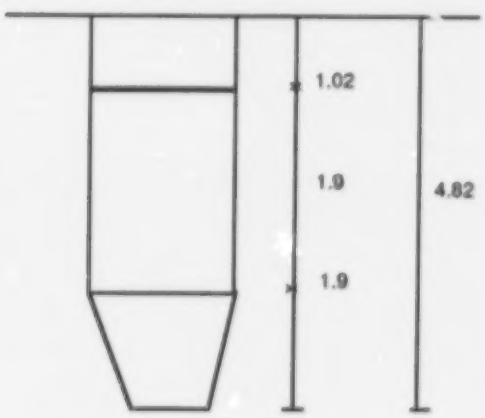
Mooring Loads

Current Forces:

$$F_D = \tfrac{1}{2} \cdot f \cdot Ap \cdot Vc^2 \cdot C_D \ (N)$$

where F_D = the total current force in newtons
ρ = density of water (1025 kg/m^3 salt water)
A_p = lateral projected area of the buoy below the waterline (m^2)
V_c = current velocity (m/sec) = 4 knots = 2 m/s
C_D = Drag Coefficient (assume = 0.5 table 4-1)

$$A_p = (0.990)(2.920) + \left(\frac{0.990 + 0.220}{2}\right)(1.9) = 4.04 \text{ m}^2$$

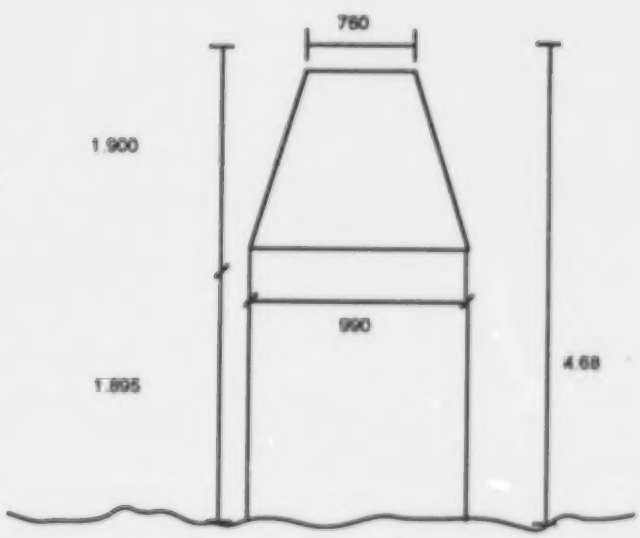


$F_D = 1/2\ (1025)\ (4.04)\ (2)^2\ (0.5)$
$F_D = 4141$ N

Wind Force

$$F_D = 1/2\, P \cdot A \cdot V^2 \cdot C_D \qquad (4.82)$$

where f = density of air (approx. 1 kg/m^3)
A = lateral projected area of hull and superstructure (m^2)
V = wind velocity (m/sec)
c = Drag on shape coefficient 0.5 for cylinder



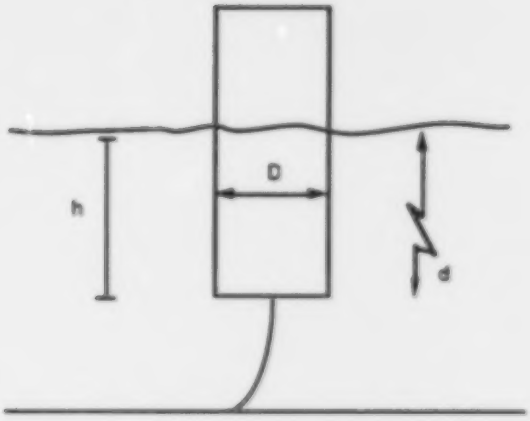
$$A = 1.9\left(\frac{0.99 + .76}{2}\right) + 1.895\,(0.99) = 3.54\ m^2$$

$$F_D = 1/2\,(1.0)\,(3.54)\,(18)^2\,(0.5)$$

$$F_D = \underline{287\ N}$$

Wave Load

$$\delta F_T = \delta F_I + \delta F_D$$



FT = total horizontal force
FD = total horizontal drag force
FI = total horizontal inertial force

$$\delta F_D = C_o \cdot f \cdot D \cdot \frac{u^2}{2} \cdot f_s$$

$$\delta F_I = C_m \cdot P \cdot \frac{D^2}{4} \cdot \dot{u}\, f_s$$

where:
CD = drag coefficient
Cm = mass coefficient
ρ = water density 1025 kg/m^3 salt water
u = horizontal vel. of water particles
$\dot{u}$ = horizontal acceleration of water particles

Apply Deep Water Conditions:

$L = Lo$ and $\frac{2\pi d}{L} \rightarrow 1.0$

$$u = \frac{\pi H}{T} e^{kz} \operatorname{Cos} \theta = \frac{\pi H}{T} e^{\left(\frac{2\pi y}{Lo}\right)} \operatorname{Cos} 2\pi\left(\frac{X}{L} - \frac{E}{T}\right)$$

$$\int_{-4.82}^{0} u^2 \cdot dy = \int_{-4.82}^{D} \left(\frac{\pi H}{T}\right)^2 \left[\exp\left(\frac{2\pi y}{Lo}\right)\right]^2 \operatorname{Cos}^2 2\pi \left(\frac{X}{L} - \frac{6}{T}\right) dy$$

$$= \left(\frac{\pi H}{T}\right)^2 \operatorname{Cos}^2 2\pi \left(\frac{X}{L} - \frac{6}{T}\right) \int_{-4.82}^{0} \exp\left(\frac{4\pi y}{Lo}\right) dy$$

$$= \left(\frac{\pi H}{T}\right)^2 \operatorname{Cos}^2 2\pi \left(\frac{X}{L} - \frac{6}{T}\right) \frac{Lo}{4\pi} \left[\exp \frac{4\pi y}{Lo}\right]_{-4.82}^{0}$$

$$L = \frac{gt^2}{2\pi} = \frac{(9.81)(10)^2}{2\pi} = 156 \text{ m}$$

$$\therefore u^2 = \left(\frac{\pi (6)}{5}\right)^2 \operatorname{Cos}^2 2\pi \left(\frac{X}{L} - \frac{t}{T}\right) \frac{39}{4\pi} |1 - .212|$$

$$u^2 = 14.21 \operatorname{Cos}^2 2\pi \left(\frac{X}{L} - \frac{t}{T}\right) (2.44)$$

$$u^2 = 34.7 \operatorname{Cos}^2 2\pi \left(\frac{X}{L} - \frac{t}{T}\right)$$

$$\int_{-4.82}^{0} \dot{u} = \frac{2\pi^2 H}{T^2} \operatorname{Sin} 2\pi \left(\frac{X}{L} - \frac{t}{T}\right) \int_{-4.82}^{0} \exp\left(\frac{2\pi y}{Lo}\right) dy$$

$$= \frac{H}{T^2} \operatorname{Sin} 2\pi \left(\frac{X}{L} - \frac{t}{T}\right) Lo \left[\exp\left(\frac{2\pi y}{Lo}\right)\right]_{-4.82}^{0}$$

$$= \frac{\pi(6)}{(5)^2} \operatorname{Sin} 2\pi \left(\frac{X}{L} - \frac{t}{T}\right) (39) |1 - 0.460|$$

$$\dot{u} = 15.88 \operatorname{Sin} 2\pi \left(\frac{X}{L} - \frac{t}{T}\right)$$

$$F_D = 1/2\ (102.5)\ (0.5)\ (0.95)\ (34.7)\ \text{Cos}^2 2\pi \left(\frac{X}{L} - \frac{t}{T}\right) = 8447\ \text{Cos}^2 2\pi \left(\frac{X}{L} - \frac{t}{T}\right)$$

$$F_I = (1025)\ (2)\ \frac{(0.95)^2}{4}\ (15.9)\ \text{Sin}\ 2\pi \left(\frac{X}{L} - \frac{t}{T}\right) = 7354\ \text{Sin}\ 2\pi \left(\frac{X}{L} - \frac{t}{T}\right)$$

$2\pi \left(\frac{X}{L} - \frac{t}{T}\right)$	$\text{Cos}^2 2\pi \left(\frac{X}{L} - \frac{t}{T}\right)$	$\text{Sin}\ 2\pi \left(\frac{X}{L} - \frac{t}{T}\right)$
0°	1	0
30°	0.75	0.5
60°	0.25	0.866
90°	0	1

Angle	0	30°	60°	90°
F_D	8447	6335	2112	0
F_I	0	3672	6368	7354
TOTAL	8447	10007	8480	7354

$F_H = \underline{7354\ N}$

Breaking Waves

$$F = 1/2 \cdot \rho \cdot C_s \cdot D \cdot L \cdot u_m^2$$

$$F = 1/2\,(1025)\,(5.5)\,(0.99)\,(9.5)\,(34.7)$$

$$F = \underline{920\ KN}$$

assume 20% = 184 KN

Mooring Cable Forces

$$\text{Tan } \theta_2 = \frac{P \cdot S}{2T_H} + \frac{P \cdot d}{2\,T_H}\left(\frac{1 + 4T_H^2}{p^2\left(s^2 d^2\right)}\right)^{1/2}$$

$T_H = 1/2\ Cd\ \rho\ Ap\ (Vc)^2$ where Cd = 0.5

ρ = 1025 kg/m^3

Ap = 4.04 m^2

Vc = 2 m/s

$T_H = 1/2\ (0.5)\ (1025)\ (4.04)\ (2)^2 = \underline{4141}\ \underline{N}$

S = chain length = water depth x 2.5 = 25m

p = wet unit weight of chain (N/m)

1 lb/ft = 1.488 kg/m

wt. of chain = $\frac{1100\ lb}{100\ ft}$ = 11 lb/ft = 16.4 kg/m

p = 16.4 (9.81) = <u>161 N/m</u>

d = water depth = 10 m

$$\tan \theta_2 = \frac{(161)\,(25)}{2\,(414)1} + \frac{(161)\,(10)}{2\,(4141)}\left(\frac{1 + 4\,(4141)^2}{(161)^2\left(25_2^2 - 10^2\right)}\right)^{1/2}$$

$\tan \theta_2 = 0.486 + 0.194\ (2.46)$

$\tan \theta_2 = \underline{0.963}$ $\theta_2 = 43.90$

$T_V = T_H \tan \theta_2 = 4141\ (0.963) = \underline{3990}\ \underline{N}$

$T = \left[(T_H)^2 + (T_v)^2\right]^{1/2} = \sqrt{(4141)^2 + (3990)^2} = \underline{5750}\ \underline{N}$

<u>Dynamic Loading</u> <u>IGNORE</u>

Summary of Forces

Total Buoy Mass	=	2950 kg
Superstructure Load	=	794 N
Current Force	=	4141 N
Wind Force	=	287 N
Wave Load	=	7354 N
Breaking Wave Load	=	184 KN
Mooring Cable Force	=	5750 N

APPENDIX D

BELL BUOY DESIGN CALCULATIONS

Parameters:

Water Line..... 2.373 m

F/B

Wave Htf..... 13 m

Wave Period..... 10 sec

Wind Vel..... 31 (m/s) 60 knots

Current Vel ..... 3.1 (m/s) 6 knots

Depth of Water..... 40.0 m

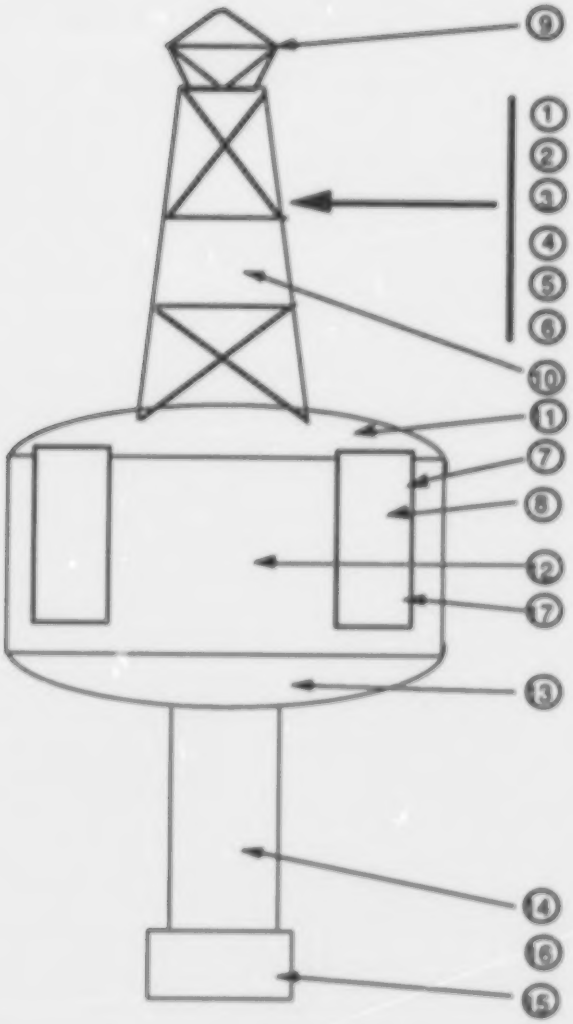
Scope of Chain..... 4:1

Length of Chain..... 160 m

Ice Mass

Since the buoy with its present configuraiton will not be stable under the ice load, we will ignore the ice mass at this time.

Item	Description	Vol (mm^3)	Mass (kg)
1	4 ∠ 6 x 65 x 8 x 1085	4.24×10^6	5.97
2	4 ∠6 x 65 x 8 x 1085	4.24×10^6	5.97
3	4 ∠125 x 75 x 8 x 1085	6.67×10^6	9.40
4	4 ∠45 x 45 x 6 x 1650	1.66×10^6	2.34
5	4 ∠45 x 45 x 6 x 1300	2.62×10^6	3.70
6	4 ∠90 x 90 x 8 x 2980	16.40×10^6	23.11
7	2 batter? holders $2[(\pi \times 560 \times 1120 \times 4) + (\pi\left(\frac{760}{2}\right)^2 \times 10) (\pi\left(\frac{560}{2}\right)^2 \times 4)$	26.81×10^6	37.78
8	Batteries 6 x 43 kg	N/A	258.00
9	Reflector	N/A	15.00
10	Bell	N/A	15.00
11	Upper shell	59.33×10^6	83.61
12	Cylinder shell	65.34×10^6	92.07
13	Lower shell	59.34×10^6	84.30
14	610 mm tube	43.72×10^6	61.60
15	Counter wt.	N/A	720.00
16	Lockwasher	Ignore	—
17	6 brackets (300 x 300 x 8)	2.16×10^6	3.04
	TOTAL		1705.00 kg


9
1
2
3
4
5
6
10
11
7
8
2
7
13
4
6
15

Marine Growth

Underwater Area Calcuation:

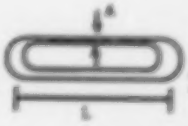
Bottom plate	$\pi\left(\frac{1000}{2}\right)^2$	=	785,398
Body of couter wt	$\pi(1000)(300)$	=	942,478
Lockwasher	$\pi(760)(80)$	=	191,009
Tube (portion u/w)	$\pi(610)(1700-380)$	=	2,529,610
Lower shell	$\pi(1380)^2$	=	5,982,849
Portion of main shell	$\pi(2600)(293)$	=	2,393,265
		=	12.824 m^2
Marine Growth @ 40 kg/m^2 x 12.824 m^2		=	513 kg

Cable Mass

Taking $\frac{3}{4}$" chain @ 100 n/m wt = 10.2 kg/m

therefore, total chain mass = 160 m * 10.2 kg/m = 1632 kg

Surface area of chain:

(assume  2 x A for surface area)

Surface area = (60 m) (2) ($\pi \frac{3}{4}$" * 0.00286 m/in) =

$\frac{3}{4}$" chain @ 100 n/m wt. = 10.2 kg/m

therefore, chain mass = 40 m x 10.2 kg/m = 408 kg

P_{water} = 1025 kg/m^3 P_{steel} = 7850 kg/m^3

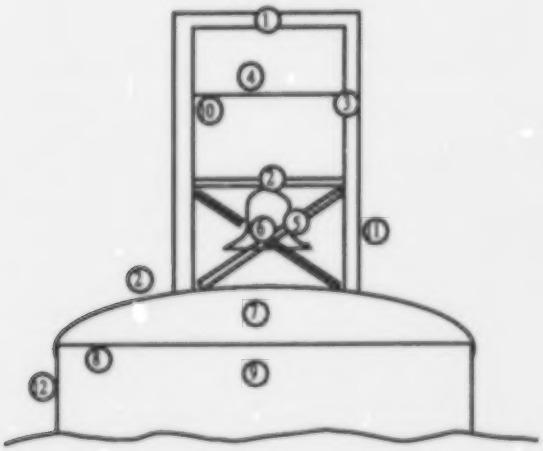
S.G. steel = $\frac{P_{steel}}{P_{water}} = \frac{7850}{1025} = 7.66$

mass of chain in water = $408 - \frac{408}{7.66} = \underline{355 \text{ kg}}$

M_T = (1705 + 355 + 513) (9.81) = <u>252. kN</u>

Superstructure Loads

$F = m \cdot w \cdot r$ where m = the mass under consideration
r = the distance of the man from the buoys static waterline
w = is the angular acceleration of the buoy caused by the wave action



Part	#	$\bar{y}$	man	$\bar{y}$ x man
1	4	3850	5.97	23000
2	4	2380	9.40	2240
3	4	2320	23.11	53600
4	1	3270	15.00	49000
5	4	1510	2.34	3530
6	1	2170	300.00	651000
7	1	700	83.61	58300
8	2	332	258.00	85600
9	1	254	58.50	14900
10	4	5320	5.64	31800
11	4	1580	3.70	5850
12	2	330	37.78	12500
			803.00	1010000

$$r = \frac{1010000}{303} = \underline{1257 \text{ mm}}$$

$m = \underline{803 \text{ kg}}$

$$w = \frac{\sigma}{T_p^2}$$

$$T_p = \frac{2k}{\sqrt{GM}}$$

K = the buoys radius of gyration about an axis through G

GM = the buoy metacentric height

G = the buoys centre of gravity

assume 2 k = 0.7 D where D is the water line diameter

therefore, $T_p = \frac{0.7\ D}{\sqrt{GM}}$ (4.3.1.1(a))

GM = 0.583 (from stability analysis)

therefore, $T_p = \frac{0.7\ (2.6)}{\sqrt{0.583}} = 2.38$ sec

$$\sigma = \frac{\pi H}{L}\left(\frac{T^2}{T^2 - T_p^2}\right)$$

where T = wave period = 10 sec

H = wave ht. = 13 m

$$L = \frac{gT^2}{2\pi} = \frac{(9.81)(10)^2}{2\pi} = 156 \text{ m} \qquad \frac{d}{L} = \frac{40}{156} = 0.25$$

therefore, cannot use deep water assumptions

$L = T\sqrt{gd} = 10\sqrt{(9.81)(40)} = 198$ m

therefore, $\sigma = \frac{\pi H}{L}\left(\frac{T^2}{T^2 - T_p^2}\right) = \frac{\pi(13)}{(198)}\left(\frac{(10)^2}{(10)^2 - (2.38)^2}\right) = 0.218$

therefore, $w = \frac{0.218}{(2.38)^2} = 0.038$

therefore F = m • w • r

= (803)(0.038)(1.260)

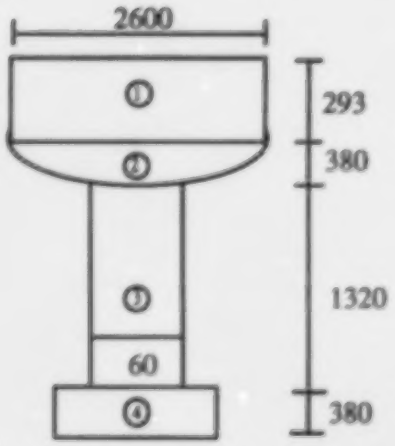
= 38.4 N

Mooring Loads

Current Forces

$$F_D = \frac{1}{2} \cdot \rho \cdot Ap \cdot Vc^2 \cdot C_D \quad (N) \qquad (4.4)$$

where: F_D = the total current force in newtons
ρ = Density of water (1025 kg/m^3 salt water)
Ap = Lateral projected area of the buoy below the water line (m^2)
Vc = Current velocity (m/sec)
C_D = Drag coefficient



A1 = (2.6)(0.293) = 0.762 m^2
A3 = (1.32)(0.61) = 0.805 m^2
A4 = (1.0)(0.38) = 0.38 m^2
A2 = = 0.624 m^2
Ap = = 2.57 m^2

Vc = 6 knots

C_D = 0.9 (assume)

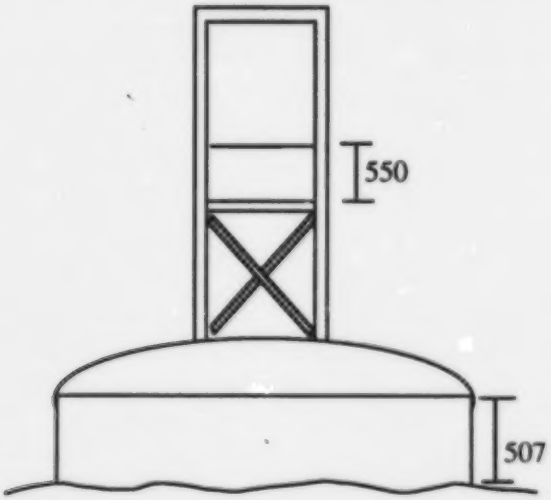
therefore, $F_D = \frac{1}{2}(1025)(2.57)(6)^2(0.9)$

= 7112 N

Wind Force

$F_D = \frac{1}{2} \rho A \cdot v^2 C_D$

where: ρ = density of air (1 kg/m^3)
A = lateral projected area
v = wind velocity (m/sec)
C_D = drag on shape coefficient



$A_{angles} = (65)(1085)(2) + (2)(90)(2980) + (2)(45)(1650) = \underline{0.826\ m^2}$

$A_{plate} = (550)(1085) = \underline{0.597\ m^2}$

$A_{upper\ shell} = \underline{0.624\ m^2}$

$A_{cylinder} = (507)(2900) = \underline{1.47\ m^2}$

v = 60 knots = 60 · (0.5144) = 30.9 m/s
C_D = 0.5 for cylinders
= 1.0 for flat plates
= 1.5 for angles

$F_{D\ angles} = \frac{1}{2}(1.0)(0.826)(30.9)^2(1.5) = \underline{592\ N}$

$F_{D\ plate} = \frac{1}{2}(1.0)(0.597)(30.9)^2(1.0) = \underline{285\ N}$

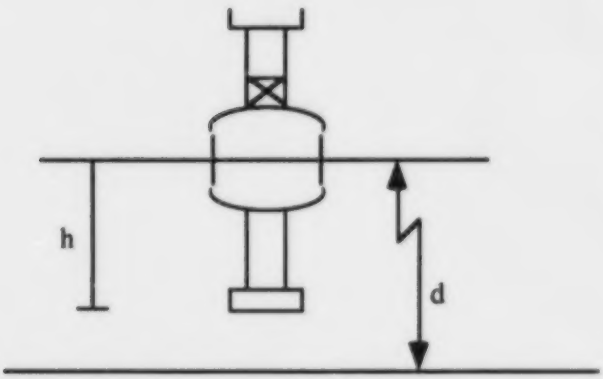
$F_{D\ body} = \frac{1}{2}(1.0)(0.624 + 1.47)(30.9)^2(0.5) = \underline{500\ N}$

$F_D = 592 + 285 + 500 = \underline{1377\ N}$

Wave Load

$\delta F_T = \delta F_I + \delta F_D$

where: F_T = total horizontal force
F_D = total horizontal drag force
F_I = total horizontal inertial force



$d = 40$ m

$$Lo = \frac{g}{2\pi} T^2 = \frac{9.81(10)^2}{2\pi} = 156 \text{ m}$$

$$\frac{d}{Lo} = \frac{40}{156} = 0.25 < 0.5$$ therefore, cannot apply deep water conditions

$$L = T\sqrt{gd} = 10\sqrt{(9.81)(40)} = 198 \text{ m}$$

$$u = \frac{\pi H}{T(Kd)} \text{Cos } \sigma$$

$$k = \frac{2\pi}{L} = \frac{2\pi}{198} = 0.0317$$

$H = Bm$

$$\int u^2 = \int \left[\frac{\pi(13)}{10(0.0317)(40)}\right]^2 \text{Cos}^2 2\pi \left(\frac{x}{L} - \frac{t}{T}\right) dh$$

$$= 10.37 \text{ Cos}^2 2\pi \left(\frac{x}{L} - \frac{t}{T}\right) h$$

$$\int \dot{u} = \frac{2\pi^2 H}{T^2(kd)} \text{Sin } 2\pi\left(\frac{x}{L} - \frac{t}{T}\right)$$

$$= \frac{2\pi^2(13)}{10^2(0.0317)(40)} \text{Sin } 2\pi\left(\frac{x}{L} - \frac{t}{T}\right) \int dh$$

$$= 2.02 \text{ Sin } 2\pi\left(\frac{x}{L} - \frac{t}{T}\right) \cdot h$$

$$F_{D\ body} = \frac{1}{2} \cdot C_D \cdot \rho \cdot D \cdot h \cdot u^2$$

$$= \frac{1}{2} \cdot (0.5) \cdot (1025)\ (2.9)\ (0.583)\ \text{Cos}^2\ 2\pi\left(\frac{x}{L} - \frac{t}{T}\right)$$

$$F_{D\ leg} = \frac{1}{2}(0.5)(1025)(.61)(1.7)(10.37)\ \ \text{Cos}^2\ 2\pi\left(\frac{x}{L} - \frac{t}{T}\right)$$

$$F_{I\ body} = \frac{1}{4} \text{Cos} \cdot \rho \cdot D^2 \cdot h \cdot \dot{u}$$

$$= \frac{1}{4}(2)(1025)(2.9)^2(0.583)(2.02)\text{Sin } 2\pi\left(\frac{x}{L} - \frac{t}{T}\right)$$

$$= 5076 \text{ Sin } 2\pi\left(\frac{x}{L} - \frac{t}{T}\right)$$

$$F_{I\ leg} = \frac{1}{4} \text{Cos} \cdot \rho \cdot D^2 \cdot h \cdot \dot{u}$$

$$= \frac{1}{4}(2)(1025)(0.61)^2(1.7)(2.02)\text{Sin } 2\pi\left(\frac{x}{L} - \frac{t}{T}\right)$$

$$= 655 \text{ Sin } 2\pi\left(\frac{x}{L} - \frac{t}{T}\right)$$

$2\pi\left(\frac{x}{L} - \frac{t}{T}\right)$	$\text{Cos}^2\ 2\pi\left(\frac{x}{L} - \frac{t}{T}\right)$	$\text{Sin } 2\pi\left(\frac{x}{L} - \frac{t}{T}\right)$
0	1.00	0.000
30	0.75	0.500
60	0.25	0.866
90	0.00	1.000

	0	30	60	90
$F_{D\ body}$	1554	1166	388	0
$F_{D\ leg}$	2756	2067	689	0
$F_{I\ body}$	0	2538	4396	5076
$F_{I\ leg}$	0	328	567	655
	4310	6099	6040	5731

$\underline{\underline{F_H = 5731\ N}}$

Breaking Waves

$F = \frac{1}{2} \cdot \rho \cdot C_S \cdot D \cdot L \cdot u^2$ assume $C_S = 5.5$

$F = \frac{1}{2}(1025)(5.5)(2.9)(10.37) = 84.8$ kN

$F_{leg} = \frac{1}{2}(1025)(5.5)(.61)(10.37) = 17.8$ kN

$F_{total} = 103$ kN

Mooring Cable Forces

$$\text{Tan } \sigma_2 = \frac{\rho \cdot S}{2T_H} + \frac{\rho \cdot d}{2T_H}\left(1 + \frac{4T_H^2}{\rho^2(S^2-d^2)}\right)^{1/2}$$

$$Tr = T_H \cdot \text{Tan } \sigma_2 \qquad (4.7.1)$$

where: S: chain length (m)
d: water depth (m)
ρ: wet, unit weight of chain (N/m)\
T_H: horizontal force

$$T = \sqrt{T_H^2 + T_V^2} \qquad (4.7.2)$$

$$T_H = \frac{1}{2} Cd \cdot \rho \cdot Ap \cdot (V_c)^2$$

$$= \frac{7}{12} N \qquad \text{from current force calculation}$$

S = chain length = 160 m
r = wet unit weight of chain = 87 N/m
d = 40 m

$$\text{Tan } \sigma_2 = \frac{(87)(160)}{2(7112)} + \frac{(87)(40)}{2(7112)}\left(1 + \frac{4(7112)^2}{(87)^2(160^2 - 40^2)}\right)^{1/2}$$

$$= 0.979 + 0.245(1.454)$$

$$\text{Tan } \sigma_2 = 1.335$$

therefore, $\sigma_2 = \tan^{-1}(1.335) = 53.17°$

$$T_v = T_H \text{Tan } \sigma_2 = (7112)(1.335)$$

$$= 9494 \text{ N}$$

$$T = \sqrt{7112^2 + 9494^2}$$

$$= 11862 \text{ N} = 11.86 \text{ kN}$$

Dynamic Loading Ignore!

Summary of Forces

Total buoy mass (does not include ice load!)	=	25.2 kN	= 2570 kg
Super structure load	=	38.4 N	
Current forces	=	7112 N	
Wind force	=	1377 N	
Wave load	=	5731 N	
Breaking waves	=	103 kN	
Mooring cable force	=	11.86 kN	

APPENDIX E

FINITE ELEMENT ANALYSIS

Model Input for Spar Buoy

Number of elements = 178
Number of Materials = 3
Number of Laminates = 4
Failure analysis = Tsai-Wu Criteria

Material Properties

#	E11	E22	μ12	μ21	G12
1	3.86E+04	8.27E+03	2.60E-01	5.37E-02	4.14E+03
2	3.86E+04	8.27E+03	2.60E-01	5.57E-02	4.14E+03
3	2.00E+05	2.00E+05	3.00E-01	3.00E-01	8.30E+04

Laminate Configuration

Laminate #01
No. of layers = 12

Layer #	Material #	Thickness (mm)	Angle (θ)
1	1	5.00 E-01	0
2	1	5.00 E-01	0
3	1	5.00 E-01	45
4	1	5.00 E-01	-45
5	1	5.00 E-01	0
6	1	5.00 E-01	0
7	1	5.00 E-01	45
8	1	5.00 E-01	45
9	1	5.00 E-01	0
10	1	5.00 E-01	0
11	1	5.00 E-01	45
12	1	5.00 E-01	-45

Laminate #02
No. of layers = 12

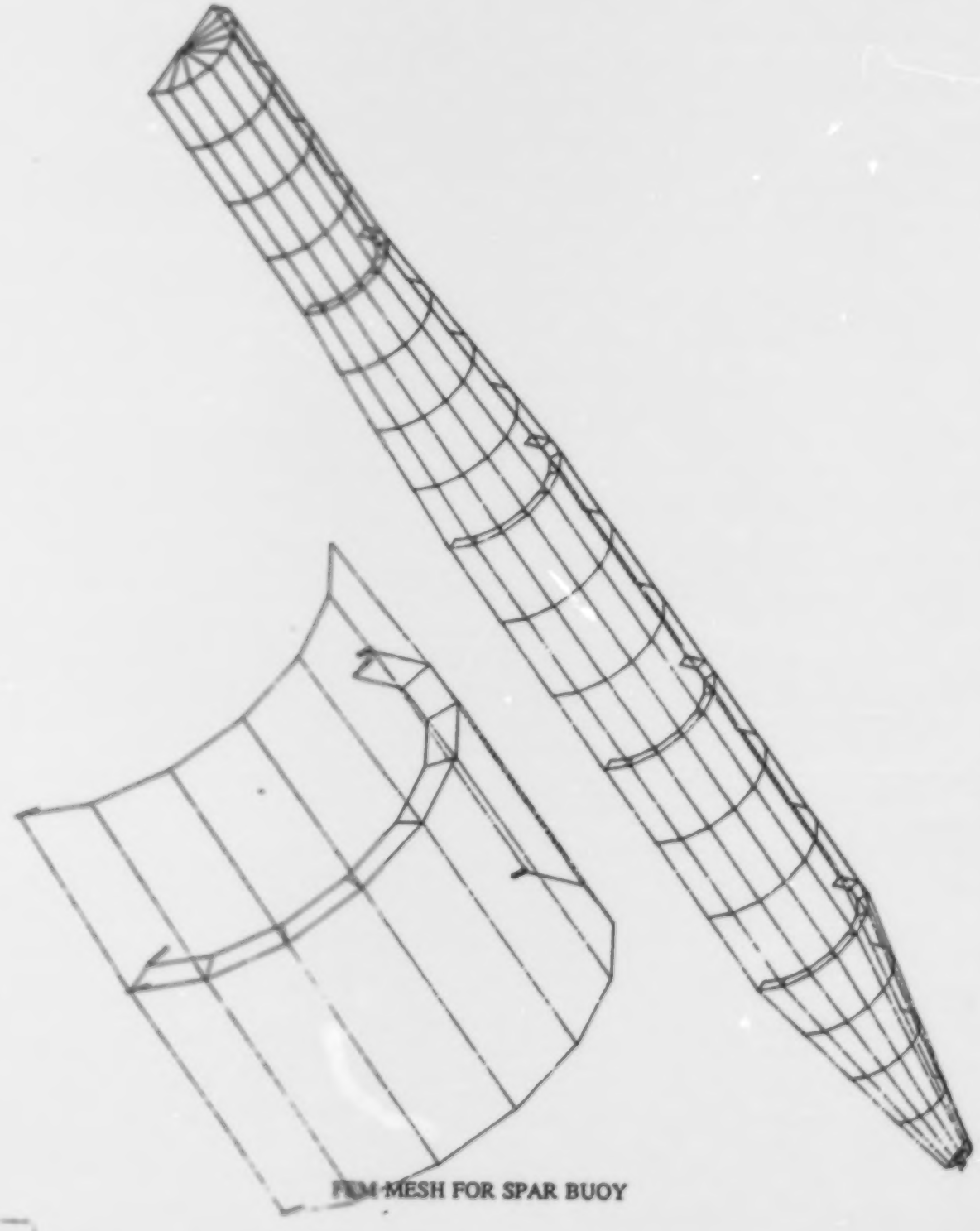
Layer #	Material #	Thickness (mm)	Angle (θ)
1	1	5.00 E-01	0
2	1	5.00 E-01	0
3	1	5.00 E-01	45
4	1	5.00 E-01	-45
5	1	5.00 E-01	0
6	1	5.00 E-01	0
7	1	5.00 E-01	45
8	1	5.00 E-01	-45
9	1	5.00 E-01	0
10	1	5.00 E-01	0
11	1	5.00 E-01	45
12	1	5.00 E-01	-45

Laminate #03
No. of layers = 8

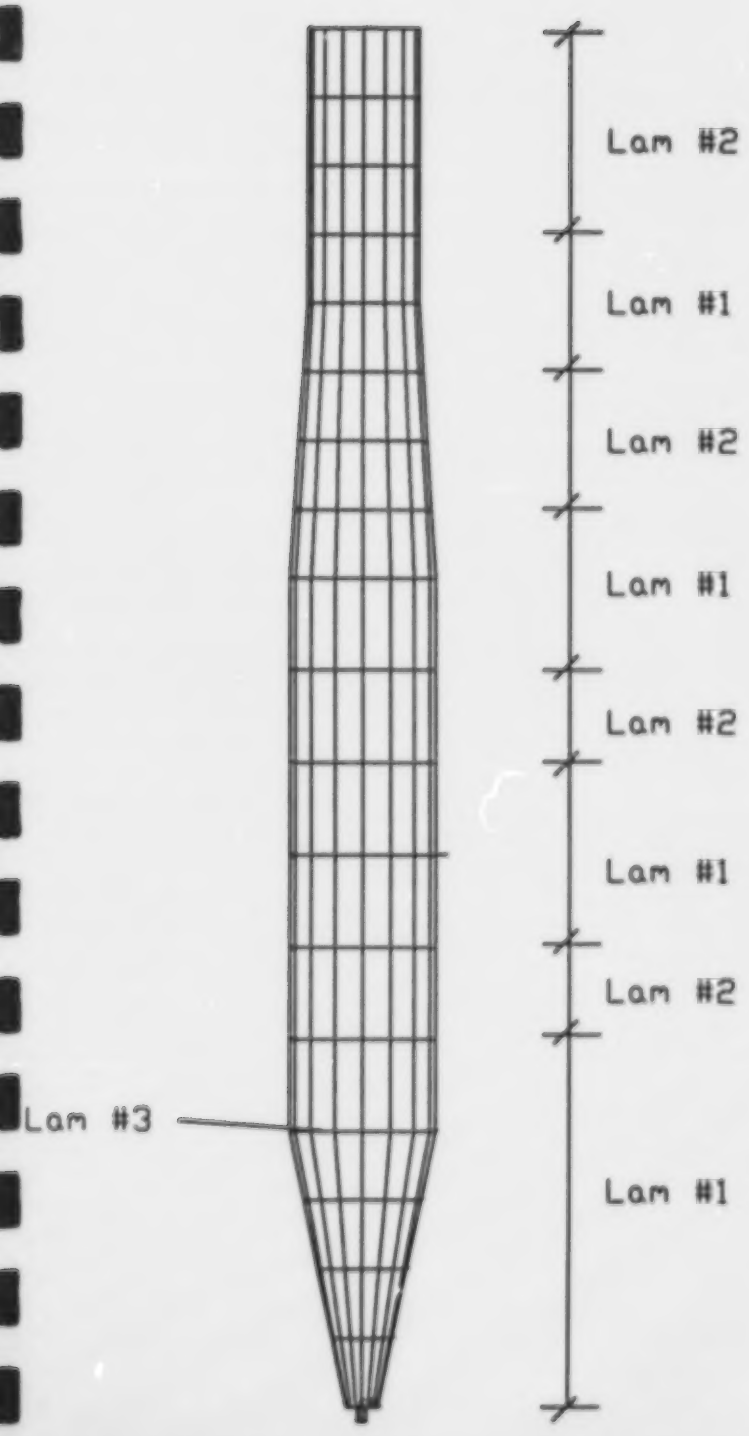
Layer #	Material #	Thickness (mm)	Angle (θ)
1	2	5.00 E-01	0
2	2	5.00 E-01	0
3	2	5.00 E-01	0
4	2	5.00 E-01	0
5	2	5.00 E-01	0
6	2	5.00 E-01	0
7	2	5.00 E-01	0
8	2	5.00 E-01	0

Laminate #04
No. of layers = 1

Layer #	Material #	Thickness (mm)	Angle (θ)
1	3	2.50 E+01	0



FEM MESH FOR SPAR BUOY



SPAR BUOY

Model Input for Light and Sound Buoy

Number of elements = 116
Number of materials = 2
Number of laminates = 4
Failure analysis = Tsai-Wu criteria

Material Properties

#	E11	E22	μ12	μ21	G12
1	2.00E+05	2.00E+05	3.00E-01	3.00E-01	8.30E+04
2	1.06E+03	6.10E+02	3.10E+01	1.18E+02	7.20E+01

Laminate Configuration

Laminate #01
No. of layers = 1

Layer #	Material #	Thickness (mm)	Angle (θ)
1	2	2.50 E+01	0

Laminate #02
No. of layers = 8

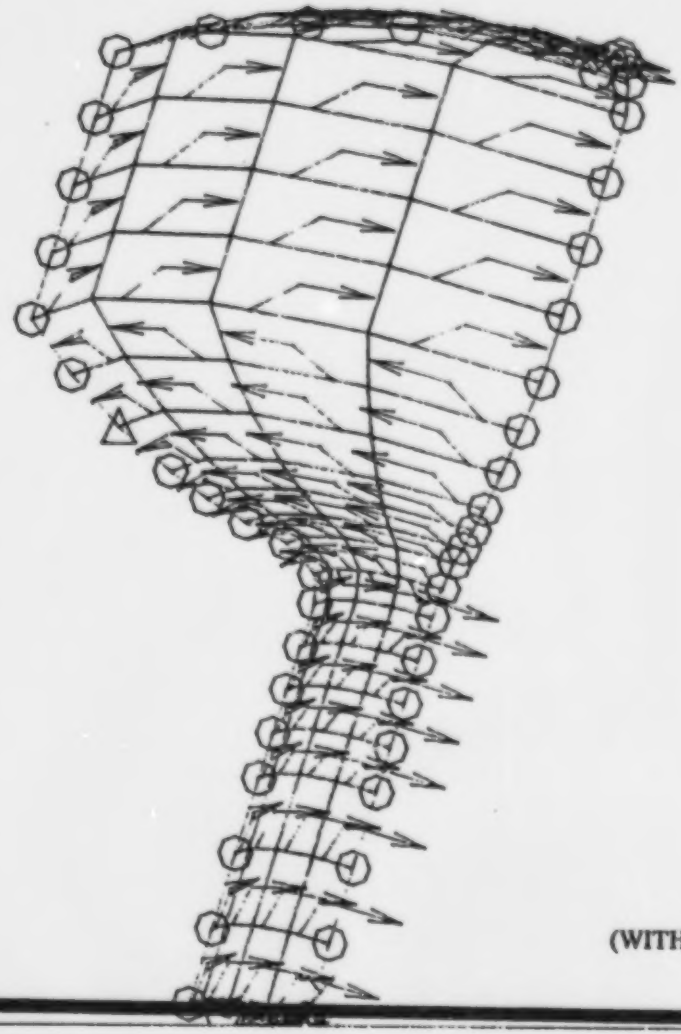
Layer #	Material #	Thickness (mm)	Angle (θ)
1	2	5.00 E-01	0
2	2	5.00 E-01	0
3	2	5.00 E-01	54.5
4	2	5.00 E-01	-54.5
5	2	5.00 E-01	0
6	2	5.00 E-01	0
7	2	5.00 E-01	54.5
8	2	5.00 E-01	-54.5

Laminate #03
No. of layers = 12

Layer #	Material #	Thickness (mm)	Angle (θ)
1	2	5.00 E-01	0
2	2	5.00 E-01	0
3	2	5.00 E-01	54.5
4	2	5.00 E-01	-54.5
5	2	5.00 E-01	0
6	2	5.00 E-01	0
7	2	5.00 E-01	54.5
8	2	5.00 E-01	-54.5
9	2	5.00 E-01	0
10	2	5.00 E-01	0
11	2	5.00 E-01	54.5
12	2	5.00 E-01	-54.5

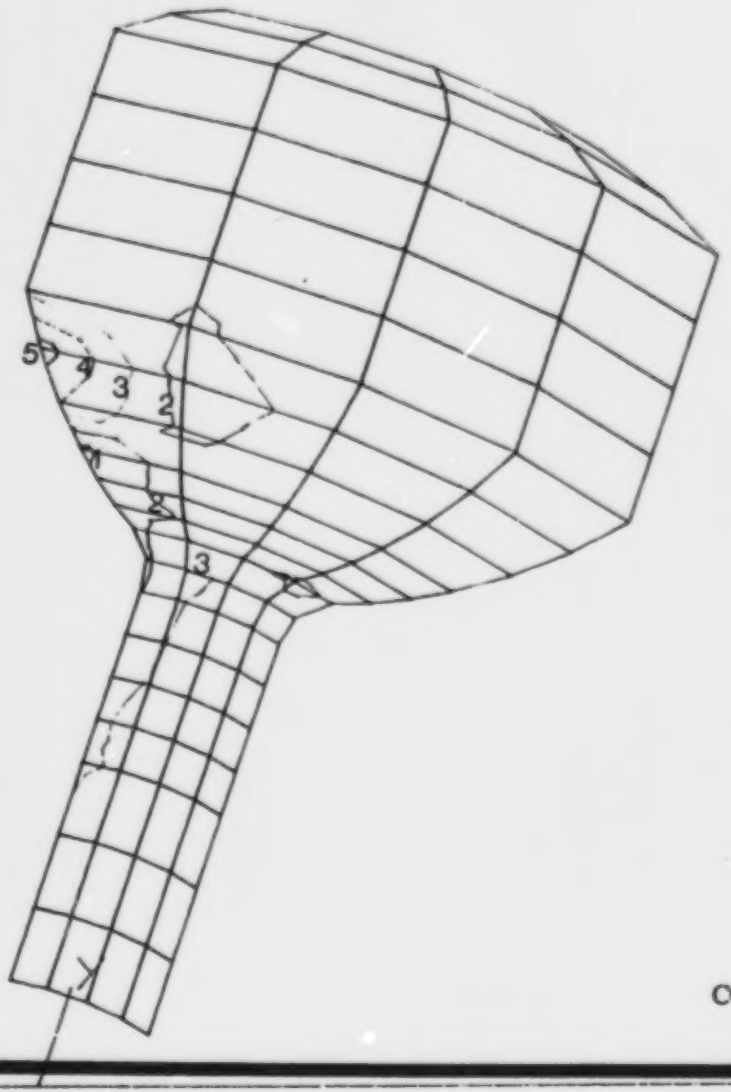
Laminate #04
No. of layers = 16

Layer #	Material #	Thickness (mm)	Angle (θ)
1	2	5.00 E-01	0
2	2	5.00 E-01	0
3	2	5.00 E-01	54.5
4	2	5.00 E-01	-54.5
5	2	5.00 E-01	0
6	2	5.00 E-01	0
7	2	5.00 E-01	54.5
8	2	5.00 E-01	-54.5
9	2	5.00 E-01	0
10	2	5.00 E-01	0
11	2	5.00 E-01	54.5
12	2	5.00 E-01	-54.5
13	2	5.00 E-01	0
14	2	5.00 E-01	0
15	2	5.00 E-01	54.5
16	2	5.00 E-01	-54.5



FEM MESH FOR BELL BUOY
(WITH DIRECTION OF FIBERS & BC)

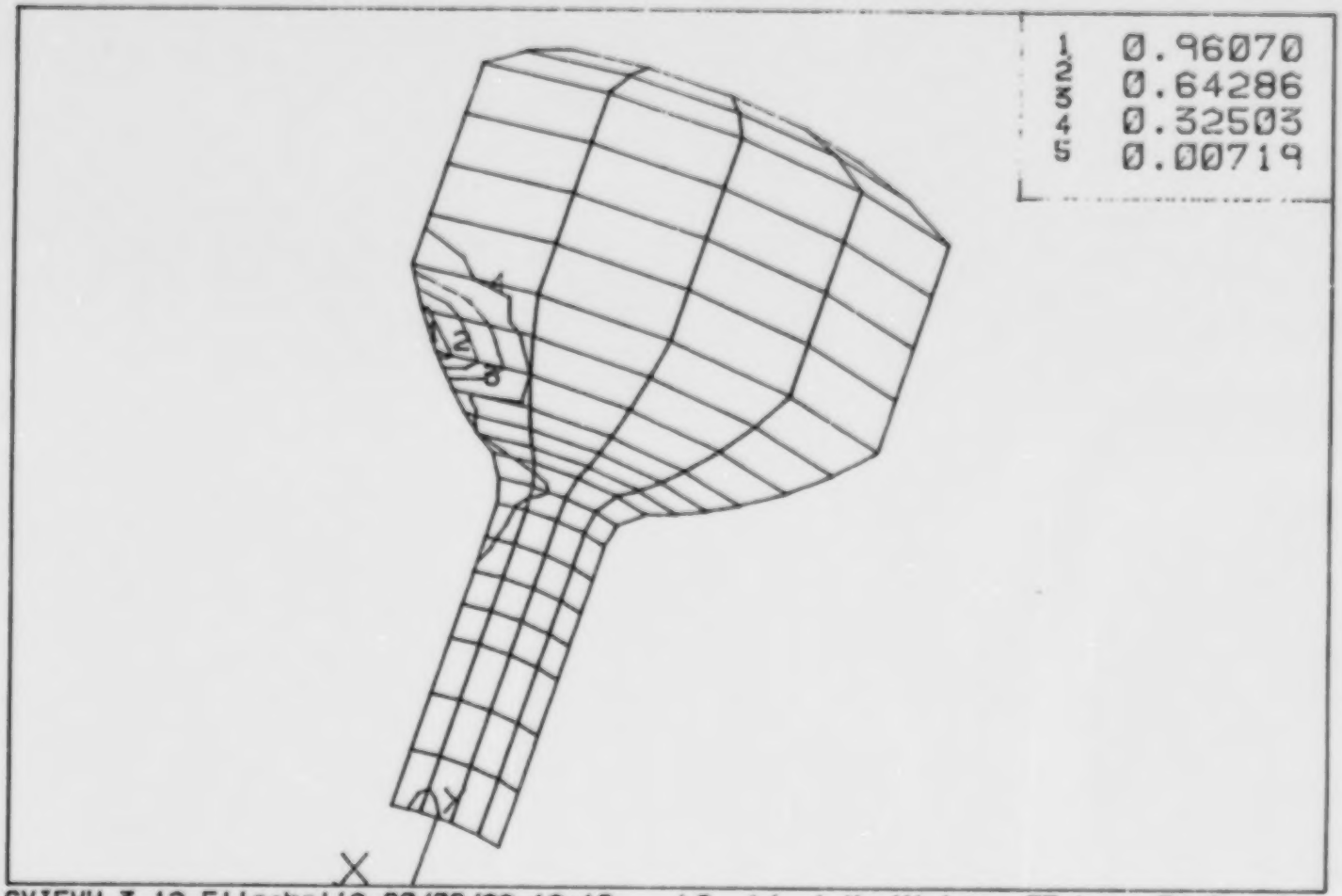
AMEC



H	358.002
7	290.626
6	223.250
5	155.874
4	88.4984
3	21.1224
2	-46.253
1	-113.62
L	-181.00

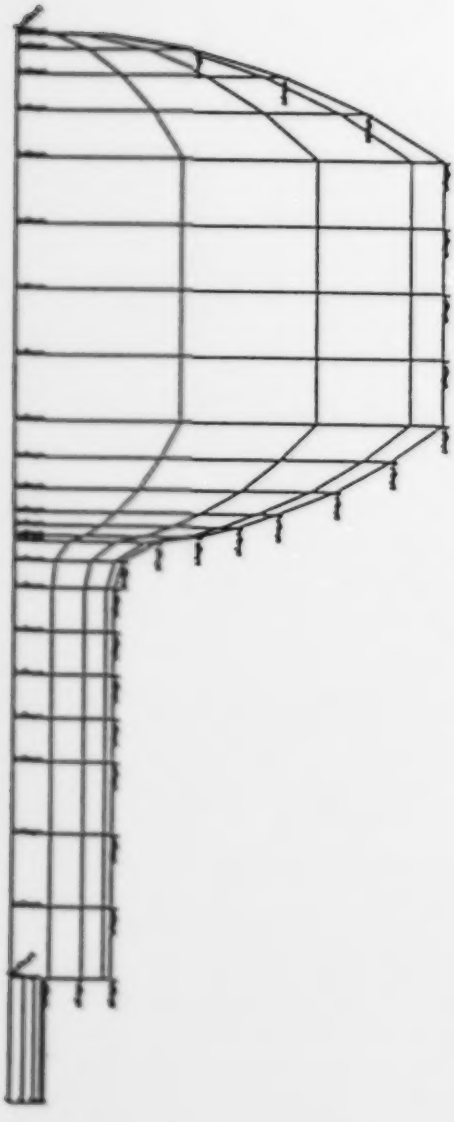
CONTOUR OF HOOP STRESSES

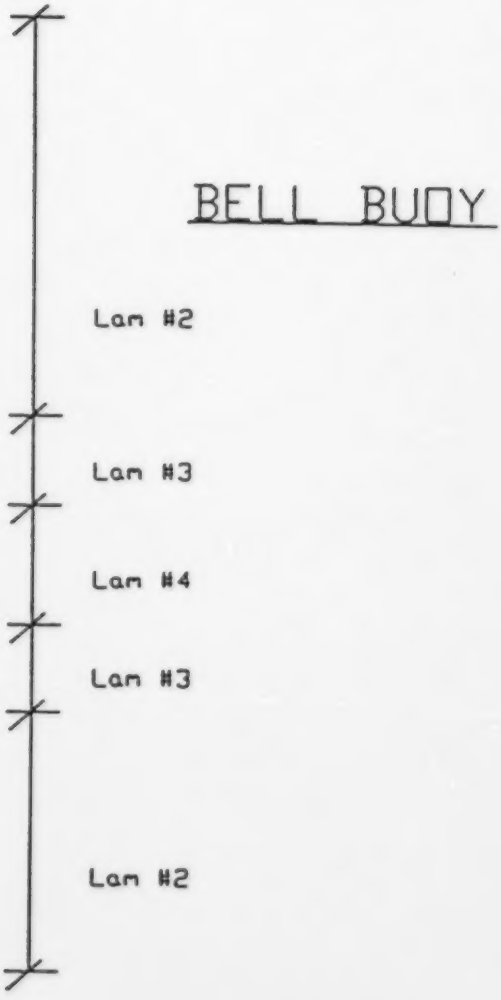
AMEC



CONTOUR OF TSAI-WU FAILURE CRITERION

AMEC




BELL BUOY
Lam #2
Lam #3
Lam #4
Lam #3
Lam #2